Research Article

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Effects of machinery trafficking in an agricultural soil assessed by Electrical Resistivity Tomography (ERT)

Abstract: Soil compaction is a serious problem, which is aggravated due to its difficulty to locate and reverse. Electrical resistivity tomography (ERT) is a non-invasive geophysical method that can be used to identify compacted areas, soil horizon thickness and assess soil physical properties. This study assesses the relationship between ERT and soil compaction. Data were collected on a 4-m transect in a fallow plot located at Bragança (Portugal). Measurements were performed before and after tillage and tractor passage. Soil samples at different depths (0-0.05, 0.05-0.1 and 0.1-0.2 m depth) were taken to determine: soil bulk density, porosity, saturated hydraulic conductivity and soil water content. The effect of tillage and tractor passage was more significant on the first 0.05 m depth. In the wheel track areas, ERT suffered a reduction of about 40%, saturated hydraulic conductivity decreased by 70% and bulk density increased by 24%. These results proved that ERT can be a useful tool for assessing soil compaction.

Keywords: Electrical Resistivity Tomography, Saturated Hydraulic Conductivity, Soil Compaction, Tillage

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1 Introduction

Soil compaction is one of the most severe forms of land degradation caused by conventional agricultural practices, negatively affecting soil physical properties (FAO 2000; European Environmental Agency 2012). It occurs even in a no-tillage system because of the compressive forces applied to soil by tractor wheels (Batey 2009). Soil compaction involves changes in soil physical properties (bulk density, strength and porosity), which can alter the mobility of elements within the soil profile (such as nitrogen and carbon cycles), causes root deformation (diminishing plant growth) and decreases soil biodiversity (Nawaz et al. 2013). Compaction is detrimental to soil structure because it crushes aggregates or combines them into large units, increasing bulk density, and decreasing the number of coarse pores (Needham et al. 2004; Delgado et al. 2007). This problem is aggravated because, compaction is mainly a sub-surface phenomenon difficult to locate and rationalize.

The spaces between and within the particles or aggregates are important for soil structure. Not only do they distribute air, water and nutrients throughout the soil, but also they sustain plant roots allowing for a healthy crop. However, compacted soil does not provide an adequate space for the storage or movement of air and water, leading to reduced water and air permeability (Mooney and Nipattasuk, 2003). Most importantly, large, continuous soil pores are lost or reduced in size, leading to slow water movement and reduced aeration. Thus, crop growth, yield and quality are negatively affected, causing economic costs to farmers. The main causes of compaction are the forces from tractor wheels and tillage implements, particularly working in moist to wet conditions when the soil is most susceptible to deformation. The main portion of the total soil compaction is caused by the first passage (Silva et al. 2008) or early passages (Sakai et al. 2008) of machinery. Compaction may occur on the land

surface, within the tilled layer, below the zone of tillage, or at greater depths (Batey 2009). Unlike erosion and salinization, which show surface evidence, compaction requires physical inputs before it is uncovered and its extent, nature and cause resolved. The economic cost and the difficulty of detection make soil compaction a serious hazard within the global "food security challenge".

Horn and Fleige (2003) developed a method to assess the effect of the passage of machinery on soil physical properties using conventional techniques. However, these methodologies are time-consuming and require a great amount of manpower. In this sense, the electrical resistivity tomography (ERT) is a non-invasive geophysical method that provides useful information about the spatial and temporal variability of many soil physical properties (Samouëlian et al. 2005) related to soil compaction. For instance, this methodology has been used to assess the effects of tillage on soil physical properties (Rossi et al. 2013; Besson et al. 2013), to describe tilled soil layers (Besson et al. 2004), to estimate soil water content (Samouëlian et al. 2005; Seladji et al. 2010; Dafonte et al. 2013) and saturated hydraulic conductivity (Farzamian et al. 2015). According to Friedman (2005), electrical resistivity (ER) depends on soil porosity, water content, structure, particle orientation and shape, particle size distribution, cation exchange capacity (CEC), temperature, etc. Since, the electric conduction occurs within the water-filled pores and at the surface of the clay particles, electrical resistivity would depend on soil bulk density and, in general terms, on soil structure (Besson et al. 2004).

The aim of this study was to assess soil compaction caused by tillage and the passage of agricultural machinery over a soil devoted to fallow; evaluating the relationship between electrical resistivity and soil compaction. In order to do that, bulk density, soil porosity and saturated hydraulic conductivity were determined using conventional methodologies and compared to the ERT measurements.

2 Material and methods

2.1 Location

The experiment was carried out on a subplot (20 m long by 4 m width) of a cultivated area at the Campus of the Polytechnic Institute of Bragança (Portugal); 41º 47' 48"N, 6º 46' 04" W, 680 m, 674 m above sea level (Figure 1). The subplot is a strip in the upper border of an annual fodder crops field, left to fallow for more than 10 years, tilled once or twice a year for adventitious vegetation control, using a tractor and implements identical to those applied in the experiment. The soil was classified as Eutric Cambisol of meta-basic rock (IUSS Working Group WRB 2014),
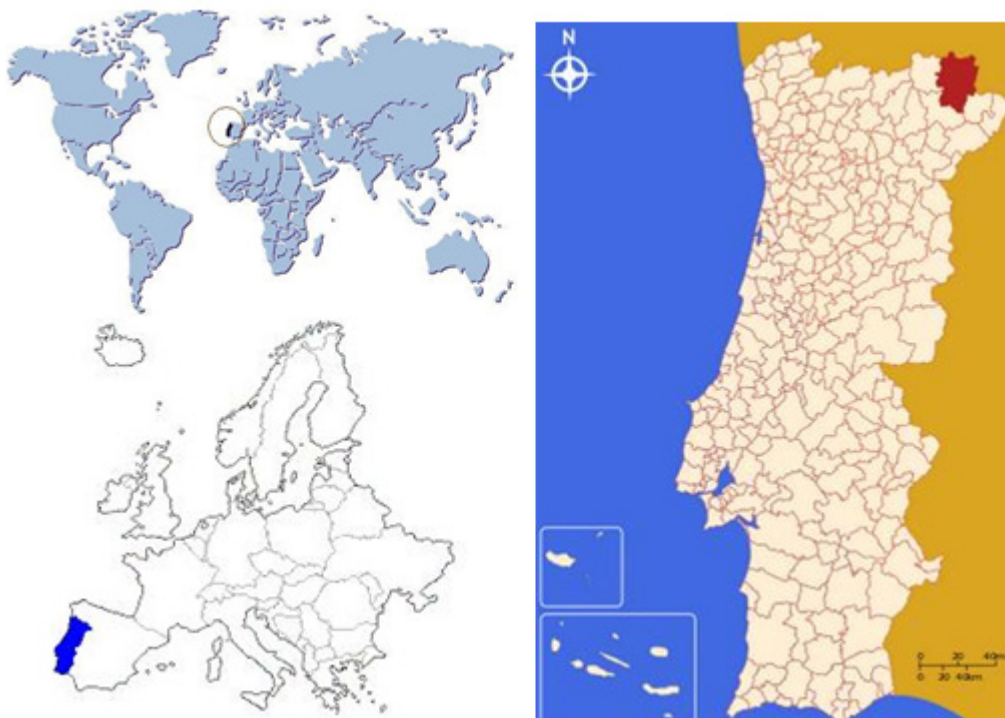

Figure 1: Location of the experimental site

gravelly, loamy-sand textured (30.24% of coarse elements; >2 mm), with a soil organic matter content about 1.4%. The climate of the study region is Csb according to Köppen climate classification (Köppen 1936). Annual precipitation is about 800 mm, with a typical Mediterranean seasonal distribution and the average annual temperature is 12ºC.

2.2 Tillage

The experiment was performed in February 2015 (mid-winter), during the wet season and the soils showed a high gravimetric water content (19.5% ±2.77), considered to be close to field capacity.

The machinery used in this study was a John Deere 5620 (4300 kg) – 53 kW tractor with 340/85 R 24 front and 420/85 R 34 rear wheels (labelled heavy). A soil pre-treatment was performed with the tractor using a 9 tines cultivator (2.43 m working width), consisting of a two-way pass over the subplot, in order to obtain a uniform soil plough -layer condition, prior to the tillage treatment. This consisted of a two-way pass with a moldboard plough, with 6 furrow, and a working width of 1.80 m, performed successively with the tractor in adjacent lanes. After this tillage operation, the tractor, implement raised, made a one-way pass over its assigned lane, compacting the soil under the wheel tracks (compaction treatment) (Figure 2).

Therefore, the experimental design compared two soil conditions (uncompacted, in the inter-wheel track, vs. compacted, in the wheel track), and their effects on soil electrical resistivity and the soil physical properties

assessed.

2.3 Soil sampling and analyses

Soil samples were collected immediately prior to (18 samples) and after (15 samples) the compaction treatment. In the former, soil samples were collected randomly over the entire subplot, whereas after the compaction treatment sampling was divided in two subsets: wheel track and inter-wheel track. Undisturbed soil cores were taken at 3 depths (0-0.05 m, 0.05-0.10 m and 0.10-0.20 m), using 100 cm^3 cylinders. Soil moisture was assessed gravimetrically (oven-dry soil at 105ºC for 48 h). Bulk density was determined with the oven-dry soil mass after permeability test. Porosity was calculated assuming 2.65 g·cm^3 as particle density. Soil saturated hydraulic conductivity was measured with a lab close-circuit constant head permeameter, measurements starting after 48 h saturation and performed at 24 h intervals for 4 consecutive days. Initial permeability was taken as the value of the first measurement after saturation, whereas final permeability was the average of the last 3 measurements. Soil core area and length were 20.10-3 m^2 and 0.05 m, respectively. Mean water head during measurements was 0.0231 m ±0.0048. The measured water level difference is used for every sample to calculate the saturated permeability coefficient (Ks – cm/h) according to Hillel (1998):
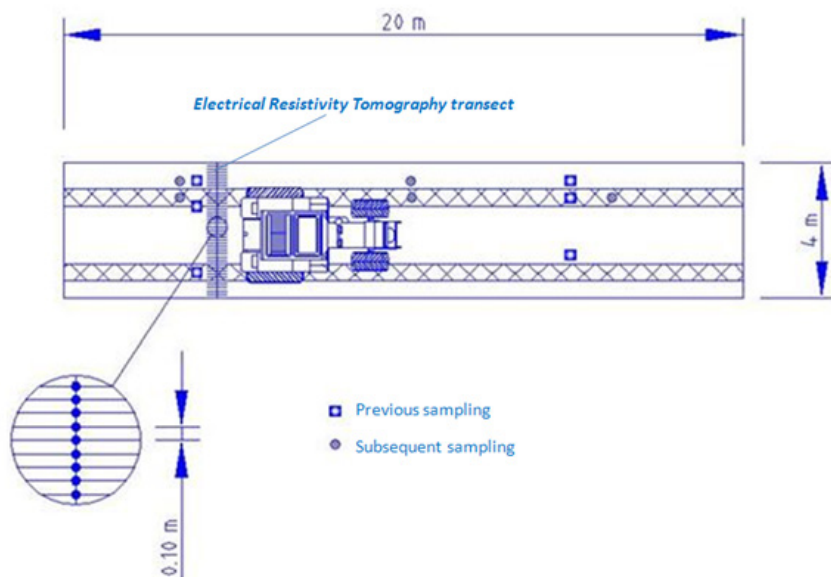
$$Ks = \frac{V*L}{A*t*h}$$

Figure 2: Scheme of the tomography assessment and soil sampling within the experimental subplot

Where Ks is the permeability coefficient or "K-factor" (cm/h); V is the volume of water flowing through the sample (cm³); L is the length of the soil sample (cm); h is the water level difference inside and outside ring holder or sample cylinder (cm); A is the cross-section surface of the sample (cm²); and t is the time used for flow through of water volume V.

2.4 Electrical Resistivity Tomography

ERT is a geophysical method that measures the electric potential differences at specific locations while injecting a controlled electric current at other locations. Depending on the position of the potential electrodes and current electrodes, several array configurations exist: Wenner, Wenner–Schlumberger, dipole–dipole, pole–pole or pole–dipole arrays are the most commonly used. Wenner array is relatively sensitive to vertical variations in subsurface resistivity, and has a high signal strength (Loke 2011; Samouëlian et al. 2005). ERT survey was carried out using a Terrameter SAS 1000 device (ABEM). The electrical resistivity was measured in a 4 m long transect, perpendicular to the traffic direction, using 40 steel electrodes spaced 0.1 m, the total length of each profile line was 4 m, using Wenner array, the effective depth was 0.85 m. ERT measurements were carried out on the same transect before and after tilling operations.

The data obtained during ERT field measurements are presented as apparent resistivity pseudo-sections. The resistivity data obtained from the field were then inverted using RES2DINV 3.59 software (Loke 2010), which is based on the regularized least-squares optimization method (Loke and Barker 1996).

Data were analyzed through a one-way ANOVA to compare each physical property and the electrical resistivity, before and after compaction, for each soil depth in the inter-wheel track and in the wheel track. When needed, Tukey HSD test ($p < 0.05$) was used for mean separation.

Ethical approval: The conducted research is not related to either human or animal use.

3 Results and discussion

3.1 Soil properties before and after tilling and tractor passage

The results of the physical soil properties, assessed before and after tillage and tractor passage are shown in Table 1. Additionally, Figure 3 depicts the relative variation of these properties before and after the machinery work. No statistically significant differences were found between depth layers, in all soil properties and conditions (before machinery work, after machinery work in the inter-wheel track and in the wheel track areas).

Total porosity, distribution of pore sizes and pore geometry are the soil characteristics affecting Ks (Hillel 1998). In our study, saturated hydraulic conductivity decreased about 84% after the tillage and tractor passage in the wheel track areas while it decreased 81% in the inter-wheel track areas. These results are consistent with the porosity reduction (17% in the wheel track areas and 12% in the inter-wheel track areas) and the bulk density

Table 1: Average values (± standard deviation) of the studied soil properties for the conditions before and after tilling and tractor passing obtained at and between the wheel tracks. Measuring depths are also shown.

Soil Property	Depth	Before	After machinery work	
	(m)	machinery work	Inter-wheel track	Wheel track
Bulk density	0-0.05	1.18a±0.16	1.35ab±0.24	1.47b±0.12
δ	0.05-0.10	1.29a±0.13	1.43ab±0.12	1.57b±0.04
(g cm⁻³)	0.10-0.20	1.47a±0.28	1.66ab±0.64	1.58b±0.09
Porosity	0-0.05	55.4a±6.2	49.1ab±8.9	44.61b±4.4
P	0.05-0.1	51.3a±5.0	46.2ab±4.5	40.78b±1.6
(%)	0.10-0.20	44.5a±10.6	37.3ab±1.6	40.26b±0.1
Saturated hydraulic	0-0.05	797.4a±1444	111.1ab±45	75.42b±101
Conductivity	0.05-0.1	364a±547	83.7ab±66	192.37b±38
Ks (cm h⁻¹)	0.10-0.20	37.8a±39	62.3ab±34	68.57b±63

For each soil property and depth, averages followed by the same letter are not significantly different (p>0.05).

increase (18% in the wheel track areas and 13% in the inter-wheel track areas).

The decrease of saturated hydraulic conductivity, porosity and the increase of bulk density were different in depth; the first 0.05 m of the soil were the most affected. In this layer, the average values of saturated hydraulic conductivity reduced from 797 cm h^{-1} (before machinery work) to 75 cm·h^{-1} (after machinery work) in the wheel track areas and to 111 cm h^{-1} in the inter-wheel track areas. Porosity decreased, in the 0-0.05 m soil depth, from 55.4% (before machinery work) to 44.6% in wheel track areas and to 49.1% in the inter-wheel track areas, confirming that this soil property is sensitive to ploughing and its usefulness as a soil-quality indicator (Fernandes et al. 2011). Bulk density average values in the same soil layer increased from 1.18 g·cm^{-3} (before machinery work) to 1.47 g·cm^{-3} in the wheel track areas and to 1.35 g·cm^{-3} in the inter-wheel track areas.

From the three soil properties measured, saturated hydraulic conductivity presented the highest variability, as shown by the coefficient of variation for the first 0.05 m depth (CV=181% prior to machinery work, CV=134% in the wheel track areas and CV=40% in the inter-wheel track areas, after machinery work). This was likely to be a consequence of the spatial variability of soil structure; especially that of the porous space. Saturated hydraulic conductivity can vary significantly in a short spatial scale since the structure of pores in soils may be affected by different rates of biological, physical, and chemical processes. In this study, tillage and, even more, tractor passage, not only reduced saturated hydraulic conductivity but also its spatial variability, indicating these physical actions resulted in more homogeneous top soil layers as their harmful effects on soil structure and

pore arrangement are intensified. As widely recognized, tillage is one of the farm operations affecting the saturated hydraulic conductivity, inducing soil degradation and promoting surface run-off and, consequently, increasing soil losses through water erosion (Mirás-Avalos et al.2009).

These results are consistent with the visual evidence of soil compaction after machinery work observed during the experiment. In addition, they show that soil structural disturbance, as that induced by compaction, is critical to water flow through the soil, reflecting sharper changes in pore size distribution and connectivity (not assessed in this study) than in total pore volume. Micro-scale heterogeneity in soil structural condition may help to explain the high data variability found, especially in the case of saturated hydraulic conductivity.

3.2 Electrical Resistivity Tomography before and after tilling and tractor passage

The ERT data obtained before and after tillage and tractor passage are shown in Figure 4. Electrical resistivity decreased after machinery work. Before trafficking, the average values at 0-0.2 m soil depth were 106.24 Ω•m (ranging from 17.97 to 204.08 Ω•m), dropping to an average of 84.20 Ω•m (ranging from 19.62 to 128.3 Ω•m), after machinery work. Soil electrical resistivity is sensitive to bulk density, hence increasing bulk density would lead to a decrease of the electrical resistivity (Besson et al. 2004). However, the relationship between resistivity and bulk density can also be insignificant when additional time-dependent variables interact with the resistivity, such as soil moisture. According to Besson et al. (2004, 2013), compacted layers presented clearly lower values
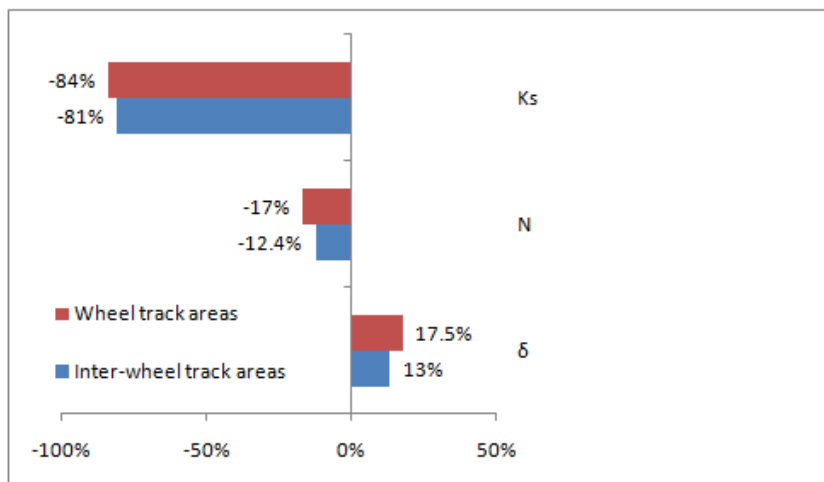

Figure 3: Relative variation (%) of Saturated Hydraulic Conductivity, Porosity and Bulk Density: before and after tillage and machinery work. Ks= Saturated Hydraulic Conductivity, P=Total Porosity, δ=Bulk Density
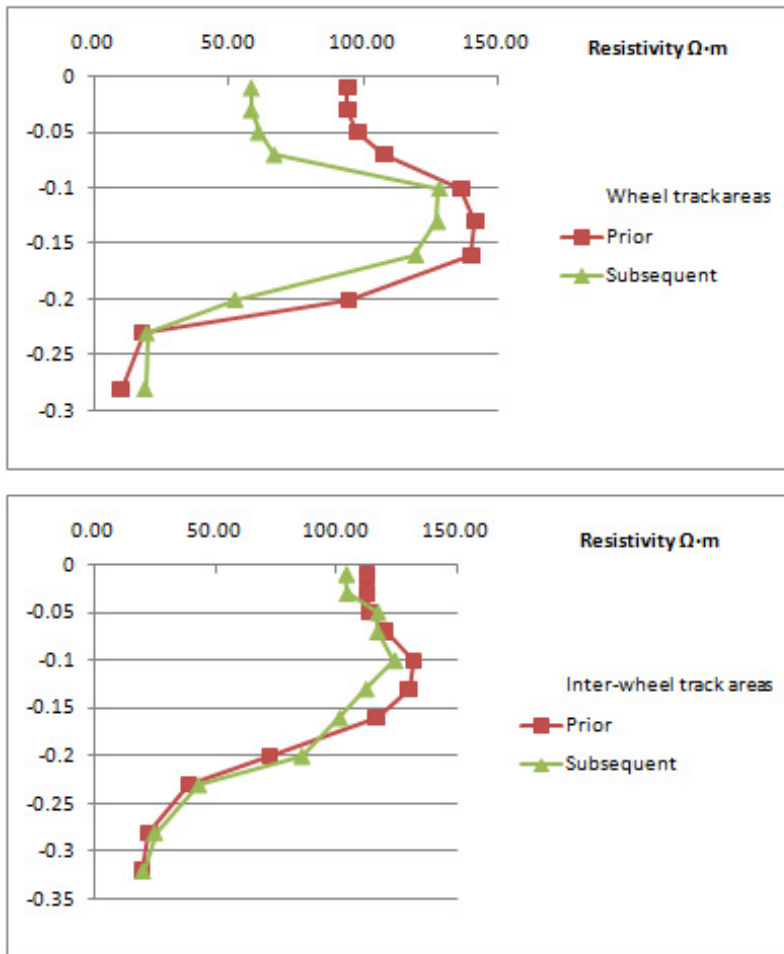
Figure 4: Resistivity (Ω•m) as a function of depth (m) in the wheel and inter wheel track areas, before and after machinery trafficking

than the non compacted ones, allowing to distinguish structural features such as plough pan or wheel tracks in field conditions using a 2D investigation.

The ERT vertical profiles obtained before and after the tillage and tractor passage are presented in Figure 5. It can be observed that in the first 0.2 m, which was the tilling depth, the soil electrical resistivity was reduced significantly in the wheel track areas while in the inter-wheel track areas the reduction is not considerable. The soil electrical resistivity (wheel track areas) decreased about 35% in the first 0.05 m of the soil, 22% in the 0.05-0.1 m and 21% in the 0.1-0.2 m (Figure 6). In the inter-wheel track areas the reduction was about 4-5% for the 3 depths studied. These results confirmed that ERT is a useful tool to assess soil compaction caused by tractor passage over an agricultural field (Basso et al. 2010)

According to Sedji et al. (2010), it is convenient to study soil compaction in dry soil because ERT better reflects bulk density changes if the soil water content is low. In

this study soil water content was 19.5%, and the difference of the soil electrical resistivity between compacted and non-compacted areas was observed clearly.

Resistivity generally decreases with soil bulk density (Abu-Hassanein et al. 1996) and increases substantially in the presence of air voids, channels and cracks (Samouëlian et al. 2005).

4 Conclusions

The usefulness of ERT for detecting soil compaction caused by the passing of agricultural machinery has been proven. ERT detected soil compaction under the wheel-tracks, where electric resistivity was reduced by 40%, saturated hydraulic conductivity decreased by 70% and soil bulk density increased 24% when compared with the conditions prior to tilling operations.

According to the obtained results, it would be possible to combine soil physical measurements and ERT profiles
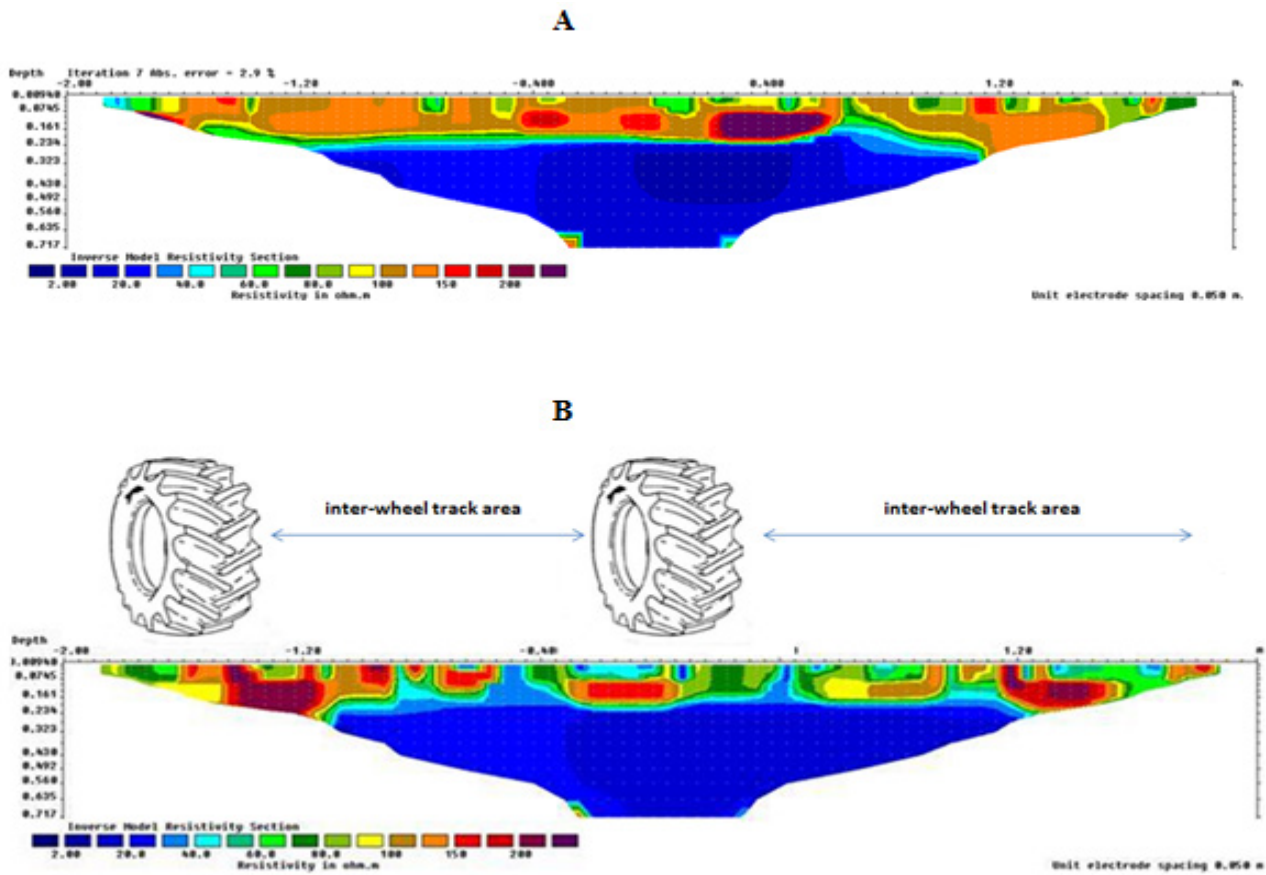
Figure 5: Electrical Resistivity profiles in the transect (using inverted RES2DINV), before and after machinery operations
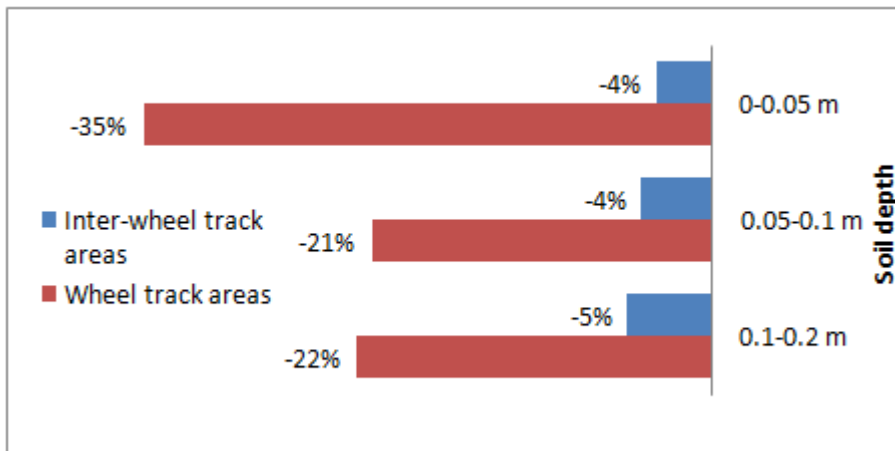

Figure 6: Relative variation (%) of Electrical Resistivity as a function of depth before and after tillage and machinery work

in 2D for characterizing compaction spatial variability in both surface and depth. In addition, future research should include ERT in 3D for a better assessment of electric resistivity variation and, hence, soil compaction.

Conflict of interest: Authors declare no conflict of interest.

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