Correlation between soil resistance penetration and soil electrical conductivity using soil sampling schemes

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Abstract
The objective of this research was to calculate the correlation between soil resistance penetration and apparent soil electrical conductivity. The studied soil was a gley cambisol sited at Lugo (Northwest Spain) at 6 ha area with forage maize under no tillage system after sowing. EC_a was measured with EM38-DD device. Soil resistance penetration was measured with an automatic static penetrometer VERIS P3000. Measured data were analyzed using classical statistics and geostatistics. The linear correlation data shows a medium negative correlation between soil resistance penetration and EC_a. The spatial variability patterns are the same for the two studied parameters. The use of soil sampling schemes techniques favours the location of measurements points for soil resistance penetration measurements.

Key Words
Chemical and physical attributes, no-tillage, geostatistics, sampling design.

Introduction
The electrical conductivity (EC) is the property that has a material to transmit or conduct electrical current (Kitchen *et al.* 1996). The apparent soil electrical conductivity (EC_a) is influenced by various factors such as soil porosity, concentration of dissolved electrolytes, texture, quantity and composition of colloids, organic matter and water content in the soil (Rhoades *et al.* 1976). Recent research found that the measurement of apparent soil electrical conductivity, the use of electromagnetic sensors, has the potential to make rapid measurements of water content in soil, the clay content of soil, cation exchange capacity and levels of exchangeable calcium and magnesium, depth horizons type "pan", organic matter content, salt content soil solution (Lesch *et al.* 2000). In this way, measurements of apparent soil electrical conductivity (EC_a) can be used to determine specific management zones. The use of farm machinery in agricultural production systems disturb the natural characteristics of the soil, often favouring the formation of compacted layers that affects to soil aeration and infiltration capacity. Kondo and Dias Junior (1999) show that the different management systems affect to the physical and mechanical soil properties of soil with different levels of compaction, depending on water content, different soil types and period of the machinery operations. According to Camargo and Alleoni (1997) the compaction of soil is a complex concept and difficult to describe and measurement, and is closely related to soil physical, chemical and biological parameters, which are important for plant development. Hill and Meza-Montalvo (1990) describe that agricultural machinery traffic during the process of agricultural production may increase the values of soil density and soil resistance to penetration to 50 %. By this reason, quantification of the soil resistance to penetration (RP, MPa) induced by soil management is an important parameter for maintaining desirable levels of production and environmental sustainability. The aim of this study was to use data from apparent soil electrical conductivity (EC_a), measured by electromagnetic induction for determining the optimized sampling scheme of soil resistance to penetration (RP) and determines the linear and spatial correlation.

Material and Methods
The study area surface is 6 ha and is located at Castro Ribeiras de Lea, Lugo, Spain (Figure 1a). The geographical coordinates of the study area are: 43º 09' 49'' N and 7º 29' 47'' W, with average elevation of 410 and average slope of 2 % (Figure 1b). The soil of the area is classified according to FAO-ISRIC (1994) as Gley Cambisol. The crop in the moment of measurement was maize for silage under no tillage system, in the last years the crop was permanent grassland for silage. The apparent soil electrical conductivity (EC_a, mS/m) was measured with an induction electromagnetic device EM38-DD (Geonics Limited). The equipment consists of two units of measurement, one in a horizontal dipole (EC_a-H) to provide and effective measurement depth of approximately 1.5 m and other one in vertical dipole (EC_a-V) with an effective measurement depth of approximately 0.75 m (McNeill 1980). The data were collected on 23/06/2008 in

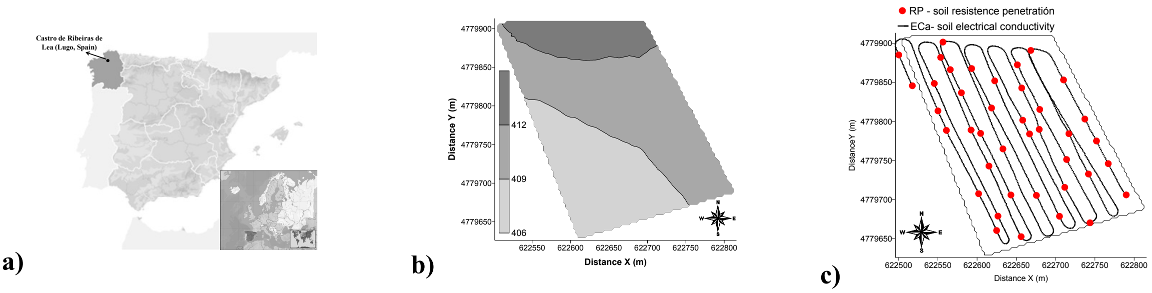

Figure 1. Location map of study area (a); digital elevation map of the study area (b); Sampling scheme of soil apparent electrical conductivity (EC_a) in 1859 points and the soil resistance to penetration (RP) at 40 points (c).

1859 points (Figure 1c), using a field computer and a GPS RTK to georeference the electrical conductivity measurements. The software ESAP 2.35 (Lesch *et al.* 2000) was also used to determine the optimum position of the 40 sample points (Figure 1c) for sampling the soil resistance penetration. The soil resistance to penetration (RP, MPa) was measured in 40 optimized sampling points using the penetrometer static Veris Profiler 3000 (Veris Technologies Inc.). In this study the soil resistance to penetration was grouped into the following layers: 0.0-0.1 m ($RP_{0.0\text{-}0.1}$), 0.1-0.2 m ($RP_{0.1\text{-}0.2}$), 0.2-0.3 m ($RP_{0.2\text{-}0.3}$), 0.3-0.4 m ($RP_{0.3\text{-}0.4}$), 0.4-0.5 m ($RP_{0.4\text{-}0.5}$), 0.5-0.6 m ($RP_{0.5\text{-}0.6}$), 0.6-0.7 m ($RP_{0.6\text{-}0.7}$), 0.7-0.8 m ($RP_{0.7\text{-}0.8}$) and 0.8-0.9 m ($RP_{0.8\text{-}0.9}$). In each sample location RP profile was measured in six near points. The RP data showed for each location is the mean of the six profiles measured. The analysis of spatial variability was performed using the semivariogram, based on the assumptions of the intrinsic hypothesis, using the program GEOSTAT (Vieira *et al.* 2002).

Results and discussion

Statistical analysis (Table 1) shows that the resistance to penetration at the layer of 0.0-0.1 m deep ($RP_{0.0\text{-}0.1}$) has a high value of coefficient of variation (67.30 %). Other data show values of coefficient of variation (CV, %) medium. The average values of the soil resistance to penetration at the different soil layers described an increase in the soil resistance to penetration (RP, MPa) in depth.

Table 1. Statistical parameters.

Equipment	Attribute	Unit	N	Minimum	Maximum	Mean	Variance	SD	CV	Skewness	Kurtosis
EM38-DD	EC_a-V	mS/m	1859	4.13	20.13	11.21	6.12	2.47	22.07	0.485	-0.243
	EC_a-H		1859	6.63	20.00	12.12	3.22	1.79	14.81	0.839	1.285
Profiler 3000	$RP_{0.0\text{-}0.1}$	MPa	140	0.30	2.47	0.64	0.18	0.43	67.30	1.169	1.858
	$RP_{0.1\text{-}0.2}$		134	1.10	3.28	2.16	0.40	0.63	29.41	-26.517	-121.478
	$RP_{0.2\text{-}0.3}$		131	1.49	3.53	2.63	0.32	0.57	21.78	-0.423	-0.677
	$RP_{0.3\text{-}0.4}$		102	1.68	4.85	3.05	0.53	0.73	23.89	0.265	0.025
	$RP_{0.4\text{-}0.5}$		84	1.74	5.54	3.12	0.94	0.97	31.17	-0.211	4.172
	$RP_{0.5\text{-}0.6}$		72	1.92	5.32	3.04	0.86	0.92	30.43	-19.154	-60.403
	$RP_{0.6\text{-}0.7}$		63	1.60	5.59	3.33	1.46	1.20	36.31	-16.549	-88.761
	$RP_{0.7\text{-}0.8}$		32	1.54	4.85	3.09	0.99	0.99	36.26	-34.572	-285.556
	$RP_{0.8\text{-}0.9}$		27	1.62	4.43	3.02	0.87	0.93	30.87	-47.972	-495.883

SD: standard deviation; CV: coefficient of variation (%).

The coefficients of linear correlation (Table 2) shows an inverse relationship between the soil apparent electrical conductivity measured with the EM38-DD (EC_a-V and EC_a-H) and the soil resistance to penetration ($RP_{0.0\text{-}0.1}$, $RP_{0.1\text{-}0.2}$, $RP_{0.2\text{-}0.3}$, $RP_{0.3\text{-}0.4}$, $RP_{0.4\text{-}0.5}$, $RP_{0.5\text{-}0.6}$, $RP_{0.6\text{-}0.7}$, $RP_{0.7\text{-}0.8}$ and $RP_{0.8\text{-}0.9}$), or the measurement points with larger EC_a values have lower values of the RP. This is because EC_a is highly dependent on soil water content (Rhoades *et al.* 1976; Lesch *et al.* 2000). Ehlers et al (1983) describe resistance to soil penetration (RP) is the main impediment to root growth, and in turn the RP is much more influenced by the soil water content and density of soil. Thus, lower soil water content reduces the values of EC_a and increases the values of RP. The best correlation was found between EC_a-V x $RP_{0.3\text{-}0.4}$ (-0.695). The existence of quadratic trend for the data is related to the existence of groundwater level near the surface in the lowest area (Figure 1b). The residuals semivariogram of electrical conductivity in the vertical dipole (EC_a-V) has an spherical model, while EC_a-H has a exponential model (Table 3). $RP_{0.0\text{-}0.1}$, $RP_{0.1\text{-}0.2}$, $RP_{0.2\text{-}0.3}$, $RP_{0.3\text{-}0.4}$ and $RP_{0.4\text{-}0.5}$ were fitted the gaussian model (Table 3). Soil resistance to penetration for deeper layers ($RP_{0.5\text{-}0.6}$, $RP_{0.6\text{-}0.7}$, $RP_{0.7\text{-}0.8}$ and $RP_{0.8\text{-}0.9}$) showed pure nugget effect. Generally the presence of pure nugget effect is because the pattern and number of measurements was not sufficient to detect the spatial variability of the studied properties. In this case, the presence of pure nugget effect for $RP_{0.5\text{-}0.6}$, $RP_{0.6\text{-}0.7}$, $RP_{0.7\text{-}0.8}$ and

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Table 2. Coefficients of linear correlation.

		--- EM38-DD ---		------------------- Profiler 3000 -------------------								
		EC_a-V	EC_a-H	$RP_{0.0\text{-}0.1}$	$RP_{0.1\text{-}0.2}$	$RP_{0.2\text{-}0.3}$	$RP_{0.3\text{-}0.4}$	$RP_{0.4\text{-}0.5}$	$RP_{0.5\text{-}0.6}$	$RP_{0.6\text{-}0.7}$	$RP_{0.7\text{-}0.8}$	$RP_{0.8\text{-}0.9}$
EM38-DD	EC_a-V	1.000										
	EC_a-H	0.748	1.000									
Profiler 3000	$RP_{0.0\text{-}0.1}$	-0.356	-0.438	1.000								
	$RP_{0.1\text{-}0.2}$	-0.498	-0.559	0.660	1.000							
	$RP_{0.2\text{-}0.3}$	-0.604	-0.593	0.411	0.847	1.000						
	$RP_{0.3\text{-}0.4}$	-0.695	-0.526	0.295	0.741	0.789	1.000					
	$RP_{0.4\text{-}0.5}$	-0.445	-0.264	0.231	0.737	0.743	0.730	1.000				
	$RP_{0.5\text{-}0.6}$	-0.518	-0.435	0.219	0.510	0.392	0.467	0.630	1.000			
	$RP_{0.6\text{-}0.7}$	-0.211	-0.396	0.430	0.611	0.304	0.317	0.382	0.782	1.000		
	$RP_{0.7\text{-}0.8}$	-0.490	-0.420	0.416	0.477	0.300	0.323	0.377	0.460	0.836	1.000	
	$RP_{0.8\text{-}0.9}$	-0.672	-0.624	0.570	0.675	0.451	0.477	0.407	0.198	0.785	0.894	1.000

Table 3. Semivariogram models and parameters.

Variable	Model	C_0	C_1	a (m)	SDR
EC_a-V Residual	Spherical	0.20	5.00	120.00	3.85
EC_a-H Residual	Exponential	0.65	2.30	110.00	22.03
$RP_{0.0\text{-}0.1}$ Residual	Gaussian	0.00	0.08	70.00	0.00
$RP_{0.1\text{-}0.2}$	Gaussian	0.00	0.55	140.00	0.00
$RP_{0.2\text{-}0.3}$	Gaussian	0.00	0.42	170.00	0.00
$RP_{0.3\text{-}0.4}$	Gaussian	0.00	0.70	140.00	0.00
$RP_{0.4\text{-}0.5}$ Residual	Gaussian	0.00	0.50	100.00	0.00
$RP_{0.5\text{-}0.6}$	Pure nugget effect				
$RP_{0.6\text{-}0.7}$	Pure nugget effect				
$RP_{0.7\text{-}0.8}$	Pure nugget effect				
$RP_{0.8\text{-}0.9}$	Pure nugget effect				

C_0: nugget effect; C_1: structural variance; a: range (m); SDR: spatial dependence ratio (%).

$RP_{0.8\text{-}0.9}$ is because the measuring equipment (Veris P3000) introduced a system security that makes the guide back to starting position if values of RP greater than 5.5 MPa (Veris Technologies Inc) are found. If the penetrometer cone reach to a soil layer with values greater than 5.5 MPa or even a stone, automatically returns to the original position, making the number of values in depth is limited due to intrinsic factors of the soil (Table 1). The values of range (a, m) are around 115.00 m to the data from EC_a, and some of 124.00 m for the data of RP. The highest value of range was for $RP_{0.2\text{-}0.3}$ (170.00 m) and the lowest value for $RP_{0.0\text{-}0.1}$ (70.00 m). The spatial dependency ratio (SDR, Table 3) shows that a high spatial dependence occurs between samples.

The maps of spatial variability (Figure 4) show that the maps of EC_a-V and EC_a-H show a similar pattern in the distribution of the contour lines. Mapping of resistance to penetration into the layer of 0.0-0.1 m deep ($RP_{0.0\text{-}0.1}$) have low values of RP in the majority of area, where the highest values of RP are concentrated in the lower right side. Map of $RP_{0.1\text{-}0.2}$ shows greatest values of RP (MPa) when compared with RP0.0-0.1.

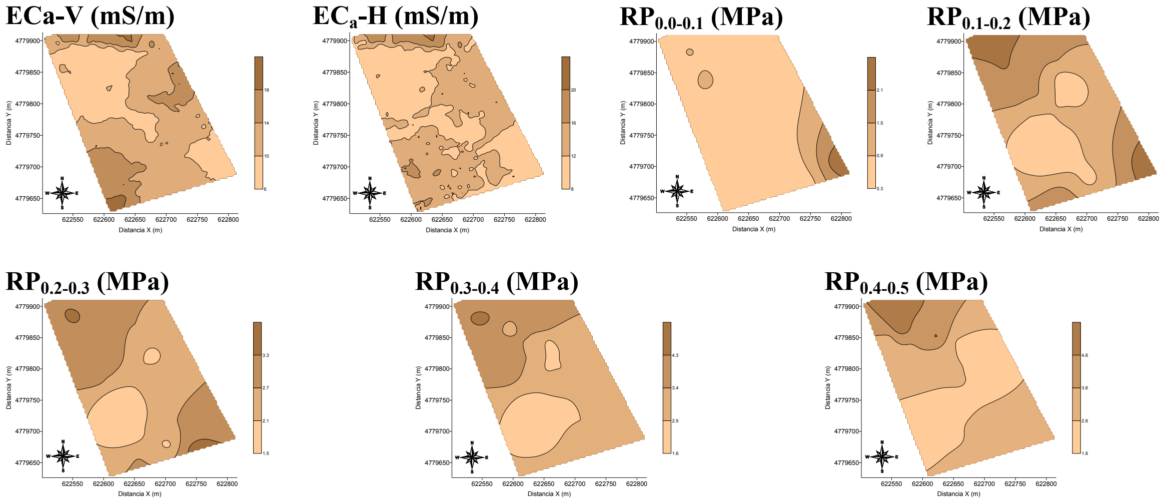

Figure 2. Maps of soil apparent electrical conductivity (EC_a-V and EC_a-H) and soil resistance penetration ($RP_{0.0\text{-}0.1}$, $RP_{0.1\text{-}0.2}$, $RP_{0.2\text{-}0.3}$, $RP_{0.3\text{-}0.4}$ and $RP_{0.4\text{-}0.5}$) obtained with ordinary kriging.

The maps of soil resistance to penetration ($RP_{0.2-0.3}$, $RP_{0.3-0.4}$ and $RP_{0.4-0.5}$) show similar pattern to $RP_{0.1-0.2}$ map. The presence of the highest values of RP (MPa) in the upper part of the area coincides with the maps of EC_a-V and EC_a-H that have lower values of EC_a in this area, corroborating the data of Table 2 that shows an inverse relationship between electrical conductivity and the soil resistance to penetration. In this way, the use of electrical conductivity data for optimizing the sampling of the soil resistance to penetration proves its efficiency mainly because the two variables are correlated with soil water content.

Conclusions

The data of EC and RP showed low values of coefficient of variation (CV, %), except for the soil resistance to penetration into the layer of 0.0-0.1 m depth that has a high value of CV (60.30 %). The gaussian model was fitted to the data of soil resistance penetration ($RP_{0.0-0.1}$, $RP_{0.1-0.2}$, $RP_{0.2-0.3}$, $RP_{0.3-0.4}$ and $RP_{0.4-0.5}$). The presence of pure nugget effect for data for soil resistance penetration in depth ($RP_{0.5-0.6}$, $RP_{0.6-0.7}$, $RP_{0.7-0.8}$ and $RP_{0.8-0.9}$) is caused by to the limited number of data in these layers once in this layer the values were often higher than the measurement value limit of the equipment (5.5 MPa). Data of apparent soil electrical conductivity (EC_a) was used to determine the optimized sampling scheme of the soil resistance penetration (RP), this methodology has proved to be efficient and capable for representing the spatial variability pattern of soil resistance penetration (RP). The maps of spatial variability shows the inverse correlation between the data of EC_a and RP, the areas with higher values of EC_a-v and EC_a-H have smaller values of RP once both properties are related to the soil water content.

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