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Running title: electrical resistivity in forest soils

# **Title: Monitoring forest soil properties with electrical resistivity**

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## Abstract

Maintenance and monitoring of soil fertility is a key issue for sustainable forest management. Vital ecosystem processes may be affected by management practices which change the physical, chemical and biological properties of the soil. This study is the first in Europe to use electrical resistivity as a non-invasive method to determine forest soil properties rapidly in the field in a monitoring purpose. We explored the correlations between electrical resistivity and forest soil properties on two permanent plots of the French long-term forest ecosystem monitoring network (International Cooperative Program Forests, Level II). We used electrical resistivity measurements to determine soil sampling locations and define sampling design. Soil cores were taken in the A horizon and analyzed for pH, bulk density, residual humidity, texture, organic matter content and nutrients. Our results showed high variability within the studied plots, both in electrical resistivity and analyzed soil properties. We found significant correlations between electrical resistivity and soil properties, notably cation exchange capacity, soil humidity and texture, even though the magnitude of the correlations was modest. Despite these levels of correlations, we were able to assess variations in soil properties without having to chemically analyze numerous samples. The sampling design based on an electrical resistivity survey allowed us to map basic soil properties with a small number of samples.

Keywords: soil fertility, forest soil monitoring, electrical resistivity

## Introduction

The Montréal Process (1999) has promoted the sustainable development of boreal and temperate forests. The workgroup involved in the process has focused on developing criteria and indicators for assessment of forest sustainable management. Criterion 4 of the process includes the maintenance of soil fertility as an essential component in the protection of soil resources. Fertility encompasses a range of soil properties: physical (compaction, erosion), chemical (biogeochemical cycles) and biological (biodiversity and biological activity) (Doelman et al. 2004; Schoenholtz et al. 2000). Quick, easy, statistically-relevant, non-destructive sampling methods are needed to assess these properties. In this context, we propose that electrical resistivity can be a useful tool.

Several studies have shown relationships between electrical resistivity measured in the field and soil properties (Friedman 2005; Samouelian et al. 2005). In agriculture, electrical methods have been used since the 1920s (see Corwin and Lesch 2005a), whereas research in forestry is rare (Robain et al. 1996; Zhu et al. 2007). In forest soils, possible background noise attributed to the presence of a vegetation layer and tree root system, the absence of tillage (less homogeneous soils) or the effect of organic matter, makes electrical study more complex. This probably explains why resistivity in forest soils has seldom been studied. In this study, we propose to use an intensive resistivity survey to design a soil sampling in forest soils and correlate soil properties with electrical resistivity. To our knowledge, this study is the first in Europe.

Many factors are correlated to resistivity such as salinity and nutrients (Rhoades et al. 1999), water content and preferential direction of water flow (Michot et al. 2003), texture-related properties (e.g. sand, clay, depth to claypans or sand layers, Corwin et al. 2003), bulk density (Corwin and Lesch 2005c), and other indirectly measured soil properties (e.g. organic matter, Fedotov et al. 2005). Soil resistivity can therefore be a non-invasive means of measuring and mapping soil properties without intensive sampling campaigns (Tabbagh et al. 2000). This method hence fulfils the requirements for assessment and monitoring methods of soil fertility (Corwin et al. 2006; Ettema and Wardle 2002; Stein and Ettema 2003).

In France, a long term forest ecosystem monitoring network (RENECOFOR: "REseau National de suivi à long terme des ECOsystèmes FORestiers", International Conference Program Forests, Level II) was established in 1992 by the National Forest Service (ONF) in order to study changes in 102 forested stands over 30 years (Ulrich 1997). The monitoring of soil properties in such long term surveys is especially challenging because sampling methods could modify the soils to a certain extent (Tabbagh et al. 2000). In particular, soil structure and properties such as bulk density may be disturbed by repeated soil core samplings. We hypothesized that electrical resistivity would be an efficient way to assess and predict soil properties without interfering with other protocols used on the plots.

Better knowledge of changes in forest soils conditions in different contexts is crucial to promote sustainable forest management in practice. We thus assumed that electrical resistivity offers an opportunity to synthesize a series of soil properties that could be related to soil fertility. In a monitoring network like RENECOFOR, this technique would allow long term repeated sampling on larger areas than currently performed, with limited impact for several soil properties such as water content, physical and chemical soil properties.

The present study aimed at testing the relevance of using electrical resistivity to map soil properties on two RENECOFOR plots located in eastern France: a montane spruce stand and a lowland oak stand. We measured electrical resistivity manually on a systematic grid, which allowed us to deal with constraints of forest ecosystems (i.e. mainly tree presence). We used the resulting resistivity map to set up a sampling design for the removal of soil core samples which we then analysed for chemical and physical properties. We determined to what extent electrical resistivity correlated with different soil properties in the field and how well this method would allow the delineation of soil properties. We then discussed the perspectives in terms of forest soil monitoring and management.

## Materials and methods

### Study sites descriptions

Working on the plots of the RENECOFOR network, we had access to extensive existing data on the plots. We chose the two study areas for their contrasting site conditions; in addition the tree species composition in the stands is representative of French mountain and lowland forests. The first study plot (EPC74: 6°20’E; 46°12 ’N) is located in the "Forêt Domaniale des Voirons" (Chablais, Haute-Savoie, France) at an elevation of 1210 m.a.s.l.. The stand is dominated by Norway spruce (Picea abies (L.) Karst). The soil type is a mixed clay-silt-sand Luvisol (IUSS Working Group WRB 2006) on a bedrock of schist and sandstone. The second study plot (CHS01: 05°14’E; 46°10’N) is located in the "Forêt Domaniale de Seillon" (Bourg-en-Bresse, Ain, France) at an elevation of 260 m.a.s.l. The stand is dominated by sessile oak (Quercus petraea Liebl.). The soil type is a Cambisol (IUSS Working Group WRB 2006) on silty deposit (Ponette et al. 1997). Both plots have a central fenced zone of approximately 0.5 ha, surrounded by a buffer zone of 1.5 ha (2 ha total).

### Resistivity survey and the resulting resistivity map

For our resistivity survey, we followed the field protocol guidelines provided by Corwin and Lesch (2005b). We chose the 4-probed Wenner configuration which is a row of 4 probes spaced at a given distance a (in our configuration, a = 25cm). We measured the electrical resistivity (ER) in half a cylinder of soil with a radius of 25cm (Samouelian et al. 2003). We considered that soil properties were homogeneous in this sampled volume. We calculated the resistivity ($\rho$ in $\Omega$.m) as follows: $\rho = K*\Delta V/I$ where $K = 2\pi a$ is a geometrical factor that depends on electrode configuration, $\Delta V$ is the potential difference (V), I the current (A) and $\Delta V/I= R$ the resistance ($\Omega$) (Samouelian et al. 2005). Due to the presence of trees, contrary to studies in agricultural fields, it was impossible to mechanize the resistivity survey. The survey was then manually processed by one man (1 day for the survey of each plot, plus 1 day for the soil sampling).

Survey locations were placed on systematic grids covering the entire plot (central and peripheral zones, 5x10 m grid in the EPC74 plot and 5x5 m grid in the CHS01 plot). We measured electrical resistivity once at each intersection of the grid lines on 26 September

(EPC74) and 8 August (CHS01), 2006 using a Landviser ERM01 Resistivity mapper (www.landviser.com). Conducting the electrical surveys in only one day allowed us to work in homogeneous weather conditions. Therefore, we did not need to correct the ER measurements for temperature which we assumed to be constant. Resistivity values higher than 10KΩ.m were considered outliers and deleted (4 values in the EPC74 plot, 5 in the CHS01 plot). These values probably resulted from poor contact between the soil and the electrodes. We processed the remaining resistivity values (431 for EPC74 and 785 for CHS01) with the ESAPv2.30 software (Lesch et al. 2000; 2003; Lesch 2005) and created an ER map of the plots interpolated from the survey data (Fig. 1).

### Soil sampling design and soil analyses

We built our soil sampling design using the Response Surface Sampling Design module of the ESAPv2.30 software (Lesch et al. 2003). This module calculates the best locations for soil core sampling sites based on electrical resistivity survey data (Corwin and Lesch 2005b). The sampling locations reflect the observed spatial variability in ER survey measurements (Lesch 2005). Our final sampling design contained 24 locations on plot EPC74 (two 12-site sub-plots) and 32 locations on plot CHS01 (one 20-site sub-plot and one 12-site sub-plot). Our soil sampling sites were located outside the central fenced zone so as not to disturb the long-term monitoring area (Fig 1). All the core samples had the same volume (250 cm3) and size (diameter=8 cm, height=5 cm) and were taken from the first A horizon (excluding organic layers). We considered that the samples were representative of the volume of soil surveyed for electrical resistivity.

On both plots, we collected the soil samples the day after conducting the electrical resistivity survey, thus avoiding variations in pedoclimatic conditions. The INRA laboratory in Arras – France (www.arras.inra.fr) analyzed the chemical and physical parameters likely to correlate with electrical resistivity: bulk density (ratio weight / volume); residual humidity at 105° C during 15 hours (NF ISO 11465); texture (amount of sand, clay and silt); organic carbon and total nitrogen contents (NF ISO 10694 and 13878); exchangeable Al, Ca, Fe, K, Mg, Mn, Na contents (Cobalthexamine – CoHex – method, ISO 11260); and pH (water). The cation-exchange capacity (CEC) and the C/N ratio were calculated from the resulting values.

## Statistical analyses

We used the Salt Mapper module of ESAP to draw the electrical maps of the plots and R v.2.9.1 (http://cran.r-project.org/) to perform correlations with electrical resistivity and regressions. We treated data from the two plots separately. Most of the soil properties were strongly skewed (Table 1), so we log-transformed the data and performed regressions using ER as the predictor variable and soil properties as response variables. The ER data was log-transformed in the EPC74 plot only. We checked the regressions' residuals for spatial auto-correlation using the Moran I test (R-package: spdep). We used a centred and scaled Principal Component Analysis (PCA, R-package: ade4) to de-correlate a subset of soil properties: CEC, total N, organic C, C/N, clay, silt and sand proportions, humidity, pH, dry and wet bulk densities. We then performed parametric correlation analyses between ER and factorial coordinates of the sample plots on the two-first axes. Although our relatively small sample sizes (24 and 32 samples) limited the power of our statistical analyses, our methods were statistically applicable and were also a good compromise between the high cost of chemical analyses and statistical relevance.

## Results

The default options of ESAP divided the resistivity data into four classes and the resulting maps (Fig. 1) show considerable electrical heterogeneity. For EPC74, the upper –left-hand corner of the plot shows a large area of high ER values whereas ER in general is relatively low on the plot (Fig. 1a). For CHS01, ER does not have any obvious spatial structure, except for a line of low electrical resistivity at the bottom of the map which corresponds to a drainage ditch (Fig. 1b). The analyses of the soil samples however showed high levels of variability within the plots (Table 1).

Proportions of exchangeable cations were highly variable. Both plots were rich in Al and Ca and their variations (expressed in % of S.D.) accounted for at least 90% of the mean.

Among the other cations, Fe concentration was the most variable and reached 182% of the mean in plot EPC74. Indicators of trophic levels (total N, organic C, organic matter and C/N ratio) varied more in plot CHS01 than in EPC74. The values of pH ranged from 4.2 to almost 7 in plot EPC 74 and from 4.1 to 5.8 in plot CHS01. The soil texture in plot EPC74 was mostly sandy but the percentage of sand varied from 14 to 77%. This clearly shows the diversity of soil conditions on the relatively small surface area (2ha) of the plot. In plot CHS01, the soil was mostly made up of silt and the texture was less variable than in the other plot (except for the drainage ditch). Variations in humidity and other factors related to soil moisture (such as weight and bulk density) accounted for around 20% of the mean in plot EPC74 and around 30% of the mean in plot CHS01.

Table 2 shows the coefficients of the regressions between ER and 19 physical and chemical soil properties among the soil properties analyzed. Results for plot EPC74 showed high levels of significance but ER only predicted around 50% of the variations of exchangeable Ca, Mg, CEC, %clay, %silt and humidity (Fig. 2a). Variability of other significantly correlated soil properties was less often predicted by ER (i.e less than 30%). The Moran test indicated significant positive spatial autocorrelation of the residuals only for percentage of silt. The residuals of the other regressions were either marginally significantly ($p<0.1$) autocorrelated (Ca, K, pH, %clay, humidity, dry weight and dry bulk density) or not autocorrelated (Table 2). For plot CHS01, levels of significance and explained variations in soil properties were less satisfactory than for EPC74. Only contents of exchangeable Al, Ca, CEC, %silt, %clay and humidity showed significant correlation coefficients with ER (Fig. 2b); ER predicted a maximum of 23% of the variations in these properties. In addition, the residuals of these regressions showed positive spatial autocorrelation for exchangeable Al and %clay ($p<0.01$), and marginally significant correlation for CEC, %silt and humidity ($p<0.1$) (Table 2).

We performed Principal Components Analyses (PCA) on a subset of soil properties to visually assess the heterogeneity of soil conditions within each plot. For both plots, the first two axes of the PCA explained more than 80% of the variance (Fig. 3). For plot EPC74, the first PCA axis differentiated humid clay soils rich in exchangeable cations from dry sandy soils poor in exchangeable cations. The second axis differentiated organic soils with low bulk density from mineral soils with high bulk density (Fig. 3a). For plot CHS01, the first PCA axis differentiated humid soils with low bulk density from sandy soils with high bulk density. The second axis differentiated acidic organic silt soils from alkaline mineral soils (Fig. 3b).

Core sample factorial coordinates on the first axis correlated significantly with ER for plot EPC74 ($\rho = 0.73$, $p<0.0001$) and marginally significantly for plot CHS01 ($\rho = 0.34$, $p = 0.06$). Correlation between ER and factorial coordinates on the second axis gave non-significant results for EPC74 and significant results for CHS01 ($\rho = -0.35$, $p = 0.05$).

## Discussion

The variations in soil ER at the two study sites allowed us to create a sampling design representative of these variations. Based on this sampling design, we found that ER correlated with some soil properties and, to some extent, represented small-scale variations in soil properties. The magnitude and the significance of these correlations differed between the study plots but our results showed similar trends: ER explained the same variations in concentrations of exchangeable Al, Ca and CEC, texture (%silt and %clay) and humidity in both study plots.

The properties of three different electrical pathways in soils actually explain the relationships between soil properties and electrical resistivity (Corwin and Lesch 2005a): (i) the liquid phase pathway through the soil water in large pores relies on dissolved solids; (ii) the solid-liquid phase pathway relies on exchangeable cations associated with clay minerals; (iii) the solid pathway relies on soil particles that are in direct contact with one another. As expected, soil humidity was significantly correlated with ER in our study. This confirmed that this water content is one of the main drivers of resistivity in soils (Corwin and Lesch 2003; Samouelian et al. 2005). The correlation between CEC and ER is due to the physical influence of exchangeable cations of the aqueous soil phase: the more exchangeable cations there are, the more electricity the soil solutions conduct (Michot et al. 2003). Bulk soil properties like texture (Farahani et al. 2005; Samouelian et al. 2005) also correlated with ER in our study. In particular, clay creates solid-liquid pathways between soil particles (Corwin and Lesch 2005a). In addition, bulk soil properties positively influence electrical pathways (and reduces electrical resistivity) in soils through particles that are in direct contact with one another (Corwin and Lesch 2005a; Triantafilis and Lesch 2005) and through an increase in water capacity (Pozdnyakov and Pozdnyakova 2002).

The electrical resistivity map allowed us to partially predict variations in forest soil on our study plots while limiting disturbance and number of samples. Our results (i.e. soil properties concerned, magnitude of the correlations) confirm those obtained in agricultural fields (Corwin and Lesch 2005c; Corwin et al. 2003; Corwin and Plant 2005; Farahani et al. 2005; Kaffka et al. 2005; Kitchen et al. 2005; Lesch et al. 2005). The ER method does appear to be adapted to forest soils despite possible background noise caused by small-scale variability (Arpin et al. 1998).

However, ER only imperfectly reflected the variations in soil properties in the studied plots and the magnitude of the correlations between ER and soil properties varied. In particular, significant Moran tests on regression residuals indicated that for content of silt (EPC74) and Al and clay (CHS01), spatial structure of the distribution of soil properties within the plots significantly explained part of the residual errors in the ER model. In addition, some soil properties crucial for defining soil fertility did not correlate with ER: for example, the C/N ratio, which is linked to functional processes involved in the decomposition of organic matter (Berg 2000). Interestingly, when we analyzed soil properties globally using PCA, ER correlated only moderately with synthetic descriptors of soil quality (i.e. factorial coordinates of the plots). This means that ER can only partially delineate soil properties at such a small scale. Despite these drawbacks, we can nevertheless say that the electrical resistivity model differentiated the fertility zones within the studied plots fairly well, including inside the central zones where soil core samples were not taken. These results offer interesting perspectives in terms of forest research and management.

Forest researchers could apply ER to soil surveys then use the resulting soil maps to set up experiments requiring homogeneous soil conditions (Johnson et al. 2005) or to create sampling designs that take local soil variability into account. Sampling designs that integrate variability in forest site conditions would result in more robust experimental approaches. In addition, ER can be used to predict variations in soil properties while avoiding heavy soil disturbance. For example, in our study plots, the fertility zones mapped with the ER method could be taken into account to design the soil monitoring scheme within the RENECOFOR network. As suggested by Corwin et al. (2006), the ER method combined with a systematic (grid) soil sampling design can provide representations of a range of soil properties, including those not well correlated with ER, because the two methods are complementary to assess soil properties. More generally, monitoring networks could use this method to track spatio-temporal changes in soil fertility: repeated ER measurements and correlation analyses can build databases for comparative analyses (Corwin and Lesch 2005c).

The ER method could also have applications in forest management, especially in cases where mechanized surveys using mobile devices are feasible. The techniques used in site-specific management in agriculture such as mechanized surveys (see Fig. 1 and 2 in Corwin and Lesch 2005b) could be transposed to forestry (see e.g. Samouelian et al. 2005). Managers could adapt tree plantations to fit soil properties. The precise relationship between soil fertility and tree growth could be investigated by setting up controlled experimental soil conditions in the field.

## Conclusions

The relations linking soil properties and electrical resistivity in two contrasting forest stands were comparable to those previously published and the models built reflected variations in soil properties to an extent comparable to those obtained in agricultural soils. Electrical resistivity is still rarely used in forests. However, our results show that this method can help differentiate levels of fertility within a small study plot and does not necessitate an intensive soil sampling campaign or cause large scale soil disturbances. Electrical resistivity appears to be an attractive non-invasive method to analyze forest soil properties at a relatively small scale and provide outcomes for forest research and management.

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## Tables and Figures

Figure 1: Interpolated ER maps of the RENECOFOR plots and soil core sampling locations (numbered plots) created with the Salt Mapper ESAP module (default settings). 1a) EPC74 plot; 1b) CHS01 plot.

Figure 2: Regressions between ER and soil properties (CEC, clay content and humidity). 2a) EPC74 plot; 2b) CHS01 plot

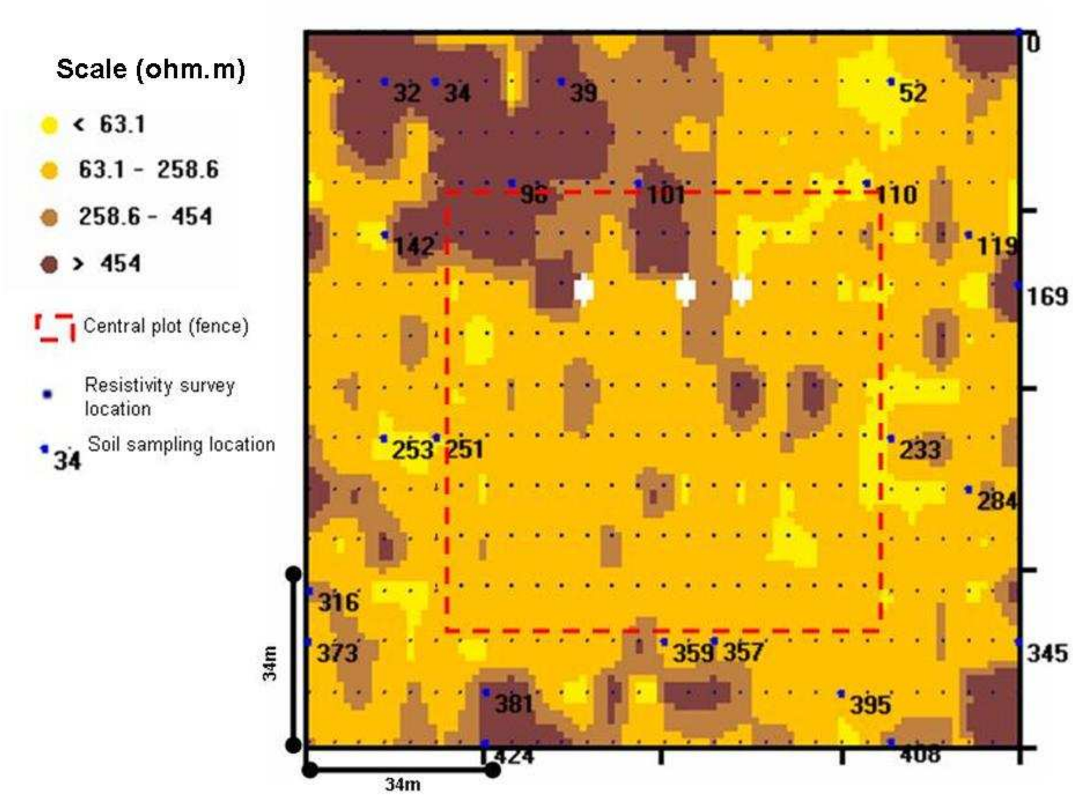
Figure 3: Principal Component Analyses (two-first factorial axes). Soil properties analysed: CEC, Total N, Organic C, C/N, Clay, Silt and Sand proportions, humidity, pH, dry and humid bulk densities. The PCA was centred and scaled. 3a) EPC74 plot; 3b) CHS01 plot.

Table 1: Physical and chemical properties of sampled soils. S.D.: standard deviation.

Table 2: Determination coefficients (r) between electrical resistivity and soil properties, regressions and Moran tests for spatial autocorrelation of the residuals results. ER data have been log-transformed for plot EPC74 only. n.s: non-significant result.

Figure 1: Interpolated ER maps of the RENECOFOR plots and soil core sampling locations (numbered plots) created with the Salt Mapper ESAP module (default settings).

1a) EPC74 plot



1b) CHS01 plot

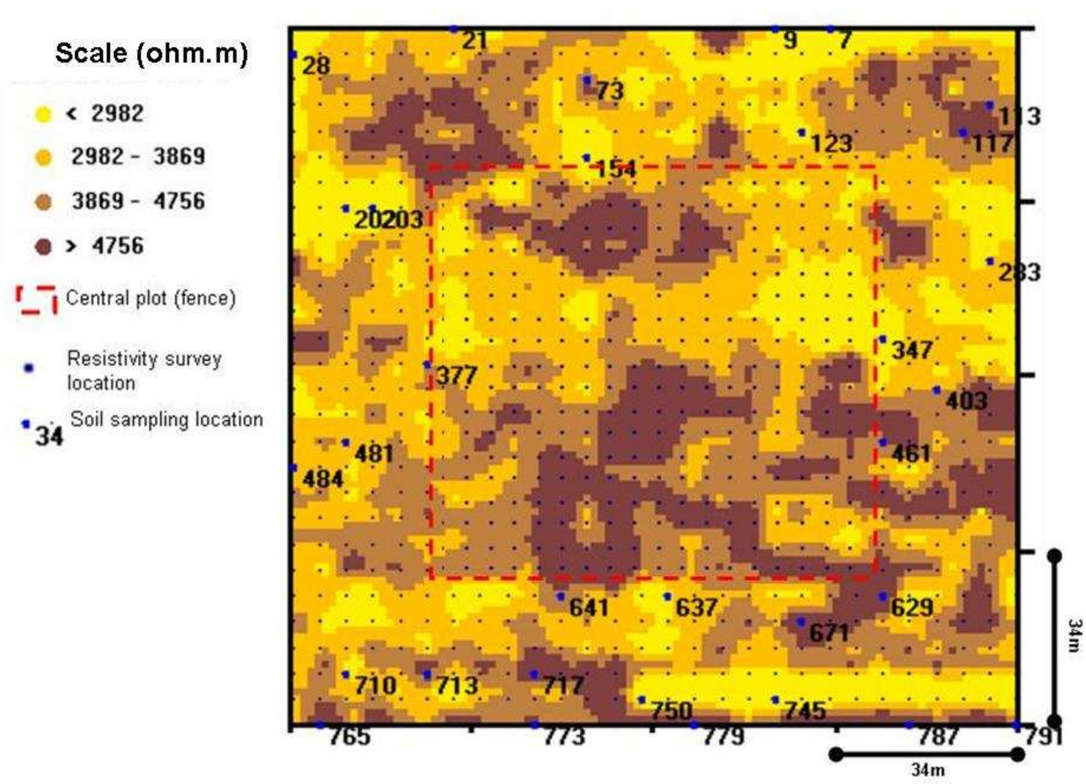
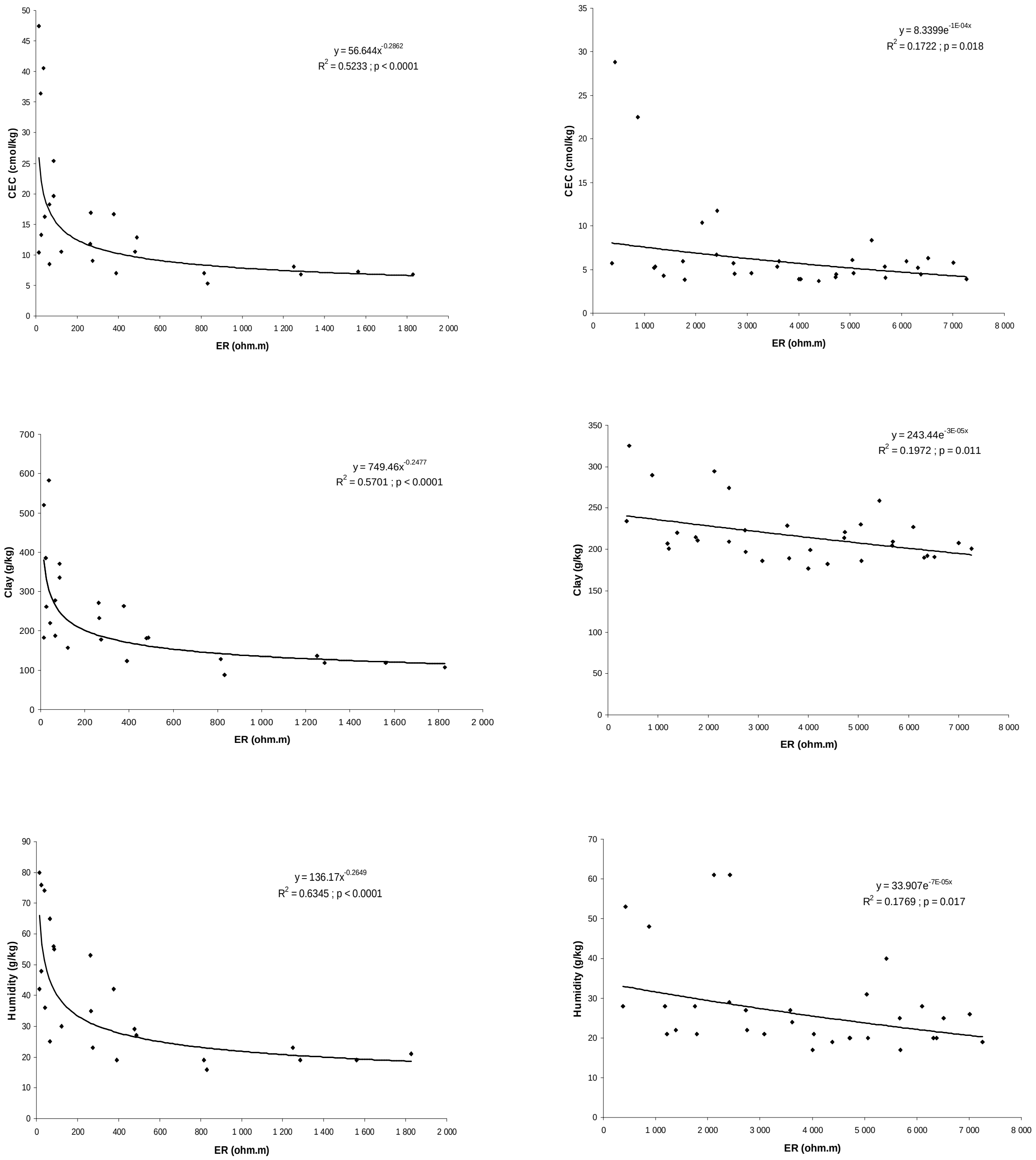


Figure 2: Regressions between ER and soil properties (CEC, clay content and humidity). 2a) EPC74 plot; 2b) CHS01 plot

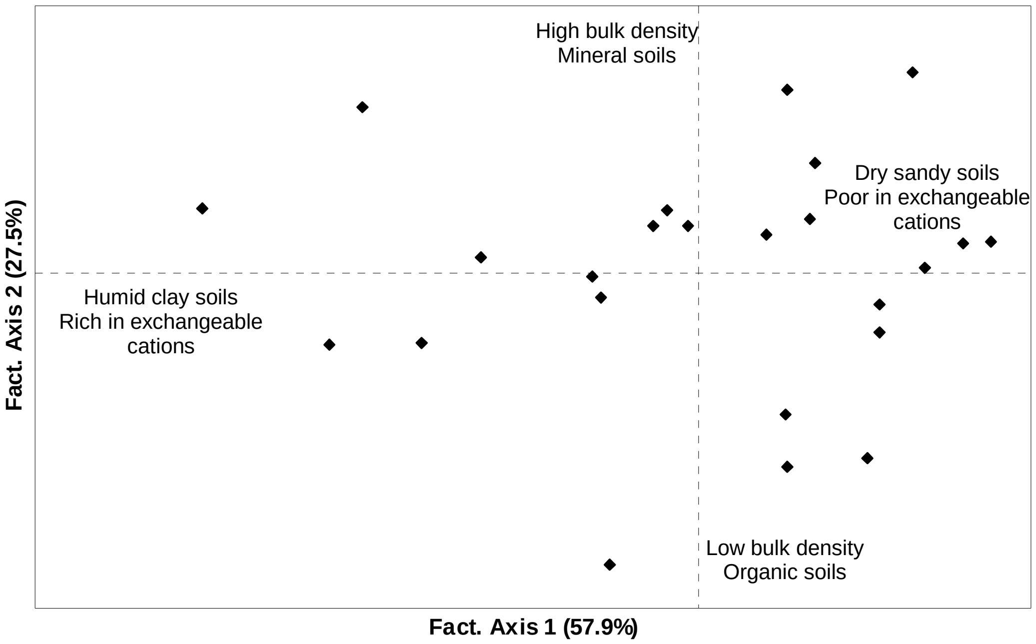


2a) plot EPC74

2b) plot CHS01

Figure 3: Principal Component Analyses (two-first factorial axes). Soil properties analysed: CEC, Total N, Organic C, C/N, Clay, Silt and Sand proportions, humidity, pH, dry bulk density. The PCA was centred and scaled.

3a) plot EPC74



3b) plot CHS01

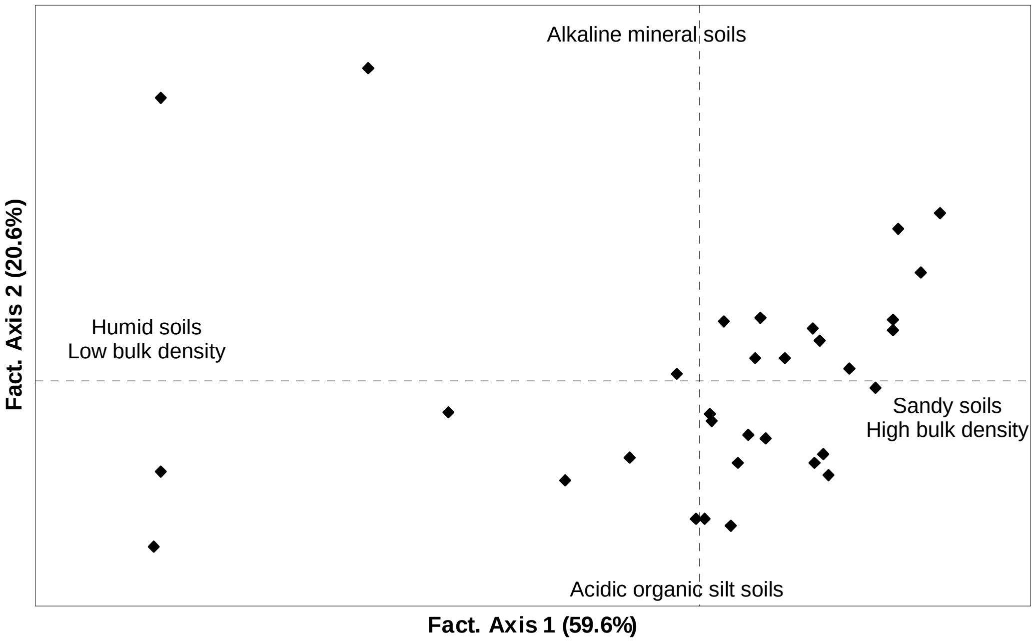


Table 1: Physical and chemical properties of sampled soils. S.D.: standard deviation.

| | EPC74 (n=24) | | | | | CHS01 (n=32) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Soil property** | **Mean** | **S.D.** | **Min** | **Max** | **Skewness** | **Mean** | **S.D.** | **Min** | **Max** | **Skewness** |
| **Chemical analyses** | | | | | | | | | | |
| Al* (cmol/kg) | 1.63 | 1.50 | 0.031 | 4.47 | 0.45 | 3.62 | 1.26 | 0.09 | 6.40 | -0.81 |
| Ca* (cmol/kg) | 12.67 | 12.01 | 1.43 | 45.80 | 1.40 | 2.27 | 5.73 | 0.25 | 27.0 | 3.49 |
| Fe* (cmol/kg) | 0.02 | 0.03 | 0.0 | 0.12 | 1.96 | 0.04 | 0.07 | 0.0 | 0.40 | 4.00 |
| Mg* (cmol/kg) | 0.75 | 0.33 | 0.33 | 1.81 | 1.32 | 0.45 | 0.40 | 0.13 | 1.69 | 1.78 |
| Mn* (cmol/kg) | 0.07 | 0.04 | 0.02 | 0.23 | 2.17 | 0.16 | 0.12 | 0.04 | 0.53 | 1.60 |
| K* (cmol/kg) | 0.35 | 0.17 | 0.16 | 0.73 | 0.91 | 0.21 | 0.12 | 0.09 | 0.58 | 1.96 |
| Na* (cmol/kg) | 0.03 | 0.02 | 0.01 | 0.07 | 0.94 | 0.03 | 0.02 | 0.02 | 0.09 | 1.83 |
| CEC (cmol/kg) | 15.51 | 11.28 | 5.29 | 47.47 | 1.53 | 6.77 | 5.33 | 3.67 | 28.79 | 3.00 |
| Total N (g/kg) | 2.96 | 1.03 | 1.78 | 5.62 | 0.95 | 3.36 | 2.10 | 1.54 | 10.10 | 1.99 |
| Organic C (g/kg) | 46.64 | 19.23 | 20.90 | 85.90 | 0.64 | 56.86 | 39.31 | 22.30 | 188.00 | 2.17 |
| C/N | 15.45 | 2.03 | 10.98 | 19.96 | -0.20 | 16.59 | 1.18 | 13.60 | 18.70 | -0.58 |
| Organic matter (g/kg) | 80.69 | 33.30 | 36.10 | 149.00 | 0.64 | 98.31 | 67.89 | 38.60 | 325.00 | 2.16 |
| pH | 5.2 | 0.7 | 4.2 | 6.9 | 0.45 | 4.6 | 0.3 | 4.1 | 5.8 | 2.07 |
| **Texture** | | | | | | | | | | |
| Gravels (0.2-0.5 cm) (g/kg) | 0.22 | 0.40 | 0.0 | 1.57 | 2.03 | 0.16 | 0.88 | 0 | 5.0 | 5.14 |
| Fine particles (<2mm) (g/kg) | 999.42 | 0.93 | 997.0 | 1000.0 | -1.17 | 998.5 | 3.85 | 984.0 | 1000 | -2.43 |
| Clay (g/kg) (%) | 233.96<br>(23%) | 127.98<br>(13%) | 88.0<br>(9%) | 583.0<br>(58%) | 1.20 | 218.59<br>(21.9%) | 34.97<br>(3.5%) | 177.0<br>(17.7%) | 325.0<br>(32.5%) | 1.41 |
| Silt (g/kg) (%) | 215.17<br>(22%) | 54.09<br>(5%) | 134.0<br>(13%) | 303.0<br>(30%) | 0.03 | 630.53<br>(63.1%) | 32.50<br>(3.3%) | 548.0<br>(54.8%) | 676.0<br>(67.6%) | -0.41 |
| Sand (g/kg) (%) | 550.88<br>(55%) | 172.35<br>(17%) | 144.0<br>(14%) | 771.0<br>(77%) | -0.75 | 150.88<br>(15.1%) | 34.14<br>(3.4%) | 56.0<br>(5.6%) | 216.0<br>(21.6%) | -0.47 |
| **Other soil properties** | | | | | | | | | | |
| Humidity (g/kg) | 38.83 | 20.11 | 16.0 | 80.0 | 0.68 | 27.78 | 11.90 | 17.0 | 61.0 | 1.70 |
| Humid weight (g) | 342.45 | 66.42 | 186.6 | 483.1 | -0.20 | 202.83 | 57.23 | 90.10 | 308.4 | -0.30 |
| Dry weight (g) | 237.89 | 54.11 | 130.85 | 349.27 | -0.10 | 167.25 | 54.41 | 56.5 | 266.0 | -0.40 |
| Dry bulk density (g/cm$^3$) | 0.952 | 0.216 | 0.523 | 1.397 | -0.29 | 0.67 | 0.22 | 0.23 | 1.06 | -0.43 |

* exchangeable cations

Table 2: Determination coefficients (r) between electrical resistivity and soil properties, regressions and Moran tests for spatial autocorrelation of the residuals results. ER data have been log-transformed for plot EPC74 only. n.s: non-significant result.

| | | Regression coefficients | | | | Moran test | |
|---|---|---|---|---|---|---|---|
| | | **r** | | **$F_{1,22}$** | **p-value** | **I** | **p-value** |
| **EPC74 (n=24)** | Al | 0.52 | ** | 8.34 | 0.009 | 0.20 | 0.42 |
| | Ca | -0.71 | *** | 22.13 | 0.000 | 1.29 | 0.10 |
| | Mg | -0.70 | *** | 21.50 | 0.000 | -0.78 | 0.78 |
| | Mn | n.s | | | | | |
| | K | -0.63 | *** | 14.70 | 0.001 | 1.47 | 0.07 |
| | Na | -0.56 | ** | 10.24 | 0.004 | -0.47 | 0.68 |
| | CEC | -0.72 | *** | 24.14 | 0.000 | 0.39 | 0.35 |
| | Organic C | n.s | | | | | |
| | Total N | -0.54 | ** | 8.98 | 0.007 | 0.40 | 0.35 |
| | C/N | n.s | | | | | |
| | pH | -0.61 | ** | 11.30 | 0.001 | 1.48 | 0.07 |
| | Silt[a] | -0.58 | ** | 14.48 | 0.003 | 2.18 | 0.01 |
| | Sand | 0.63 | *** | 29.18 | 0.001 | 0.91 | 0.18 |
| | Clay | -0.76 | *** | 38.20 | 0.000 | 1.48 | 0.07 |
| | Humidity | -0.79 | *** | 13.34 | 0.000 | 1.29 | 0.10 |
| | Humid weight | n.s | | | | | |
| | Dry weight | 0.56 | ** | 9.83 | 0.005 | 1.29 | 0.10 |
| | Dry bulk density | 0.49 | * | 6.90 | 0.015 | 1.44 | 0.07 |
| | | **r** | | **$F_{1,30}$** | **p-value** | **I** | **p-value** |
| **CHS01 (n=32)** | Al | 0.35 | * | 4.23 | 0.049 | 2.433 | 0.007 |
| | Ca | -0.48 | ** | 9.13 | 0.005 | 0.126 | 0.45 |
| | Mg | n.s | | | | | |
| | Mn | n.s | | | | | |
| | K | n.s | | | | | |
| | Na | n.s | | | | | |
| | CEC | -0.42 | * | 6.25 | 0.018 | 1.508 | 0.07 |
| | Organic C | n.s | | | | | |
| | Total N | n.s | | | | | |
| | C/N | n.s | | | | | |
| | pH | n.s | | | | | |
| | Silt[a] | 0.45 | ** | 0.04 | 0.009 | 1.442 | 0.08 |
| | Sand | n.s | | | | | |
| | Clay | -0.44 | * | 7.37 | 0.011 | 2.640 | 0.004 |
| | Humidity | -0.42 | * | 6.45 | 0.017 | 1.561 | 0.06 |
| | Humid weight | n.s | | | | | |
| | Dry weight | n.s | | | | | |
| | Dry bulk density | n.s | | | | | |

[a] data has not been log-tranformed

*p<0.05; **p<0.01; ***p<0.001