

1 Running title: electrical resistivity in forest soils

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

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14 **Abstract**

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

32 **Keywords:** soil fertility, forest soil monitoring, electrical resistivity

33 **Introduction**

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

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

53 Many factors are correlated to resistivity such as salinity and nutrients (Rhoades et al.
54 1999), water content and preferential direction of water flow (Michot et al. 2003), texture-
55 related properties (e.g. sand, clay, depth to claypans or sand layers, Corwin et al. 2003), bulk
56 density (Corwin and Lesch 2005c), and other indirectly measured soil properties (e.g. organic
57 matter, Fedotov et al. 2005). Soil resistivity can therefore be a non-invasive means of
58 measuring and mapping soil properties without intensive sampling campaigns (Tabbagh et
59 al. 2000). This method hence fulfils the requirements for assessment and monitoring

60 methods of soil fertility (Corwin et al. 2006; Ettema and Wardle 2002; Stein and Ettema
61 2003).

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

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

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

86

87 **Materials and methods**

88 **Study sites descriptions**

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

101 **Resistivity survey and the resulting resistivity map**

102 For our resistivity survey, we followed the field protocol guidelines provided by Corwin and
103 Lesch (2005b). We chose the 4-probed Wenner configuration which is a row of 4 probes
104 spaced at a given distance a (in our configuration, $a = 25\text{cm}$). We measured the electrical
105 resistivity (ER) in half a cylinder of soil with a radius of 25cm (Samouelian et al. 2003). We
106 considered that soil properties were homogeneous in this sampled volume. We calculated
107 the resistivity (ρ in $\Omega\cdot\text{m}$) as follows: $\rho = K \cdot \Delta V / I$ where $K = 2\pi a$ is a geometrical factor that
108 depends on electrode configuration, ΔV is the potential difference (V), I the current (A) and
109 $\Delta V / I = R$ the resistance (Ω) (Samouelian et al. 2005). Due to the presence of trees, contrary
110 to studies in agricultural fields, it was impossible to mechanize the resistivity survey. The
111 survey was then manually processed by one man (1 day for the survey of each plot, plus 1
112 day for the soil sampling).

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

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

125 **Soil sampling design and soil analyses**

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

137 On both plots, we collected the soil samples the day after conducting the electrical
138 resistivity survey, thus avoiding variations in pedoclimatic conditions. The INRA laboratory in
139 Arras – France (www.arras.inra.fr) analyzed the chemical and physical parameters likely to
140 correlate with electrical resistivity: bulk density (ratio weight / volume); residual humidity at
141 105° C during 15 hours (NF ISO 11465); texture (amount of sand, clay and silt); organic
142 carbon and total nitrogen contents (NF ISO 10694 and 13878); exchangeable Al, Ca, Fe, K,

143 Mg, Mn, Na contents (Cobalthexamine – CoHex – method, ISO 11260); and pH (water). The
144 cation-exchange capacity (CEC) and the C/N ratio were calculated from the resulting values.

145 **Statistical analyses**

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

160

161 **Results**

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

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

171 Among the other cations, Fe concentration was the most variable and reached 182% of the
172 mean in plot EPC74. Indicators of trophic levels (total N, organic C, organic matter and C/N
173 ratio) varied more in plot CHS01 than in EPC74. The values of pH ranged from 4.2 to almost
174 7 in plot EPC 74 and from 4.1 to 5.8 in plot CHS01. The soil texture in plot EPC74 was
175 mostly sandy but the percentage of sand varied from 14 to 77%. This clearly shows the
176 diversity of soil conditions on the relatively small surface area (2ha) of the plot. In plot
177 CHS01, the soil was mostly made up of silt and the texture was less variable than in the
178 other plot (except for the drainage ditch). Variations in humidity and other factors related to
179 soil moisture (such as weight and bulk density) accounted for around 20% of the mean in plot
180 EPC74 and around 30% of the mean in plot CHS01.

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

196 We performed Principal Components Analyses (PCA) on a subset of soil properties to
197 visually assess the heterogeneity of soil conditions within each plot. For both plots, the first
198 two axes of the PCA explained more than 80% of the variance (Fig. 3). For plot EPC74, the

199 first PCA axis differentiated humid clay soils rich in exchangeable cations from dry sandy
200 soils poor in exchangeable cations. The second axis differentiated organic soils with low bulk
201 density from mineral soils with high bulk density (Fig. 3a). For plot CHS01, the first PCA axis
202 differentiated humid soils with low bulk density from sandy soils with high bulk density. The
203 second axis differentiated acidic organic silt soils from alkaline mineral soils (Fig. 3b).

204 Core sample factorial coordinates on the first axis correlated significantly with ER for
205 plot EPC74 ($\rho = 0.73$, $p < 0.0001$) and marginally significantly for plot CHS01 ($\rho = 0.34$, $p =$
206 0.06). Correlation between ER and factorial coordinates on the second axis gave non-
207 significant results for EPC74 and significant results for CHS01 ($\rho = -0.35$, $p = 0.05$).

208

209 **Discussion**

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

217 The properties of three different electrical pathways in soils actually explain the
218 relationships between soil properties and electrical resistivity (Corwin and Lesch 2005a): (i)
219 the liquid phase pathway through the soil water in large pores relies on dissolved solids; (ii)
220 the solid-liquid phase pathway relies on exchangeable cations associated with clay minerals;
221 (iii) the solid pathway relies on soil particles that are in direct contact with one another. As
222 expected, soil humidity was significantly correlated with ER in our study. This confirmed that
223 this water content is one of the main drivers of resistivity in soils (Corwin and Lesch 2003;
224 Samouelian et al. 2005). The correlation between CEC and ER is due to the physical
225 influence of exchangeable cations of the aqueous soil phase: the more exchangeable cations
226 there are, the more electricity the soil solutions conduct (Michot et al. 2003). Bulk soil

227 properties like texture (Farahani et al. 2005; Samouelian et al. 2005) also correlated with ER
228 in our study. In particular, clay creates solid-liquid pathways between soil particles (Corwin
229 and Lesch 2005a). In addition, bulk soil properties positively influence electrical pathways
230 (and reduces electrical resistivity) in soils through particles that are in direct contact with one
231 another (Corwin and Lesch 2005a; Triantafilis and Lesch 2005) and through an increase in
232 water capacity (Pozdnyakov and Pozdnyakova 2002).

233 The electrical resistivity map allowed us to partially predict variations in forest soil on
234 our study plots while limiting disturbance and number of samples. Our results (i.e. soil
235 properties concerned, magnitude of the correlations) confirm those obtained in agricultural
236 fields (Corwin and Lesch 2005c; Corwin et al. 2003; Corwin and Plant 2005; Farahani et al.
237 2005; Kaffka et al. 2005; Kitchen et al. 2005; Lesch et al. 2005). The ER method does
238 appear to be adapted to forest soils despite possible background noise caused by small-
239 scale variability (Arpin et al. 1998).

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

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

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

274

275 **Conclusions**

276 The relations linking soil properties and electrical resistivity in two contrasting forest stands
277 were comparable to those previously published and the models built reflected variations in
278 soil properties to an extent comparable to those obtained in agricultural soils. Electrical
279 resistivity is still rarely used in forests. However, our results show that this method can help
280 differentiate levels of fertility within a small study plot and does not necessitate an intensive
281 soil sampling campaign or cause large scale soil disturbances. Electrical resistivity appears

282 to be an attractive non-invasive method to analyze forest soil properties at a relatively small
283 scale and provide outcomes for forest research and management.

284

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 366

367 **Tables and Figures**
368

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

372

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

375

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

379

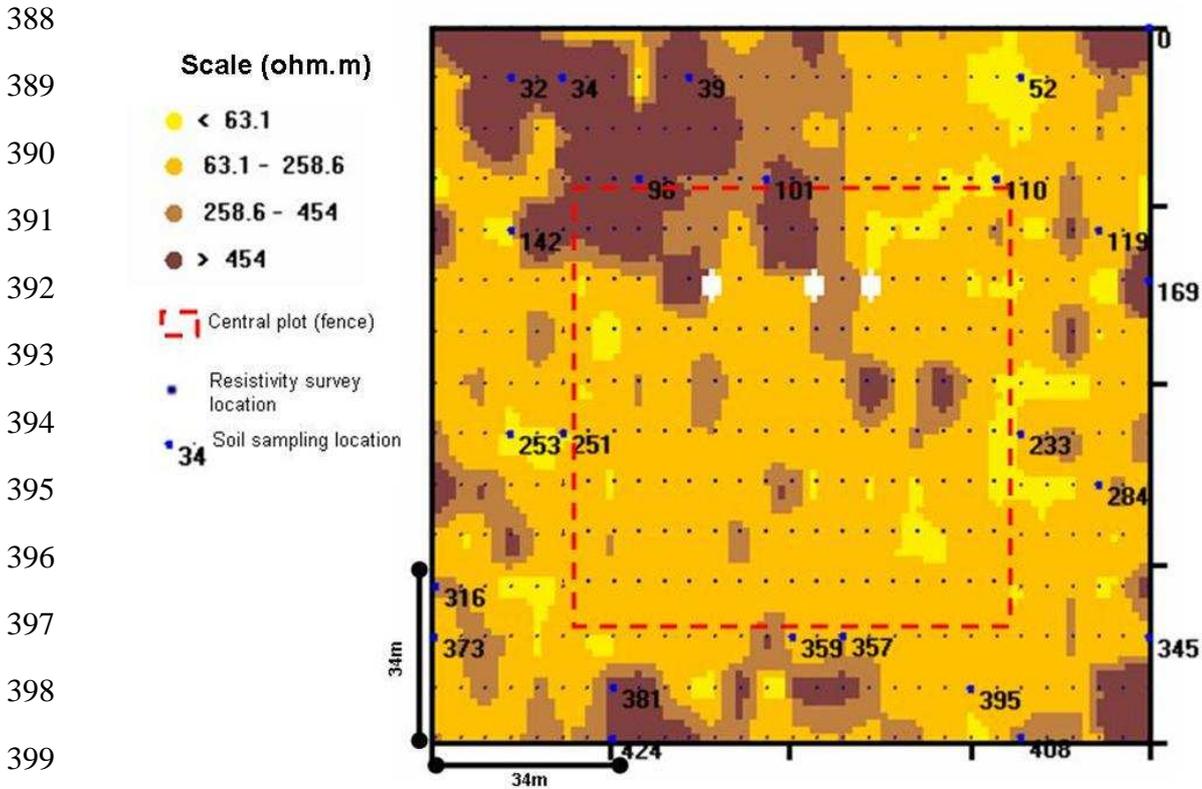
380 Table 1: Physical and chemical properties of sampled soils. S.D.: standard deviation.

381

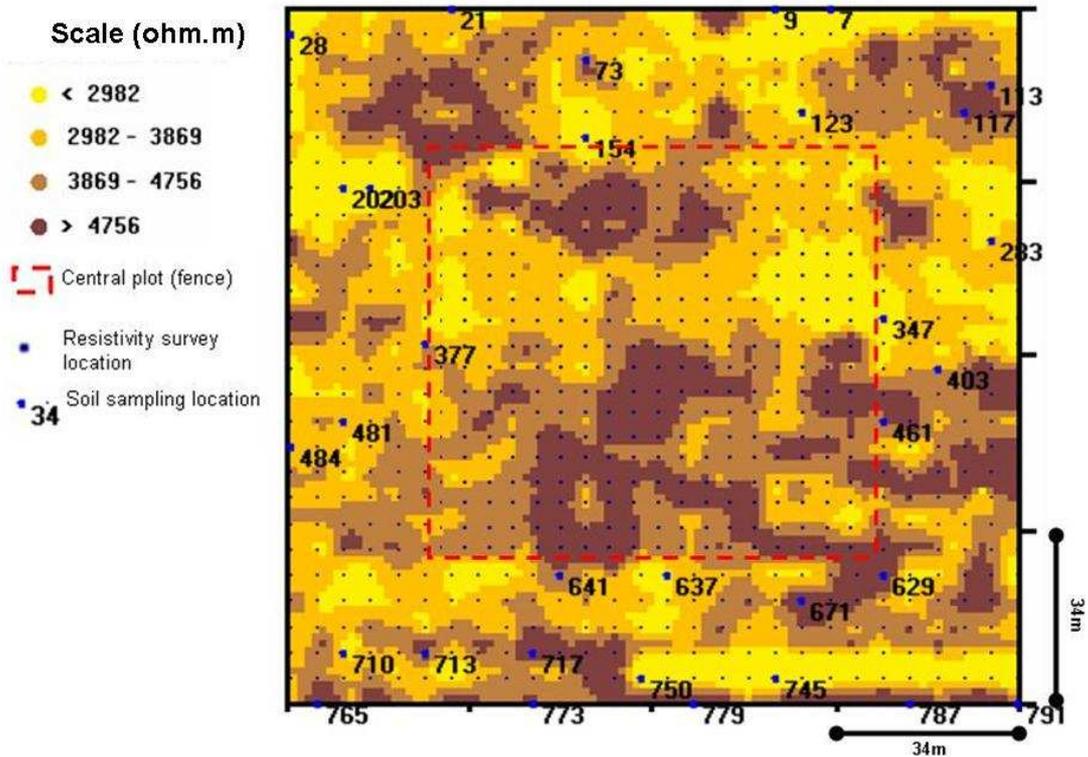
382 Table 2: Determination coefficients (r) between electrical resistivity and soil properties,
383 regressions and Moran tests for spatial autocorrelation of the residuals results. ER data have
384 been log-transformed for plot EPC74 only. n.s: non-significant result.

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

387 1a) EPC74 plot



400 1b) CHS01 plot

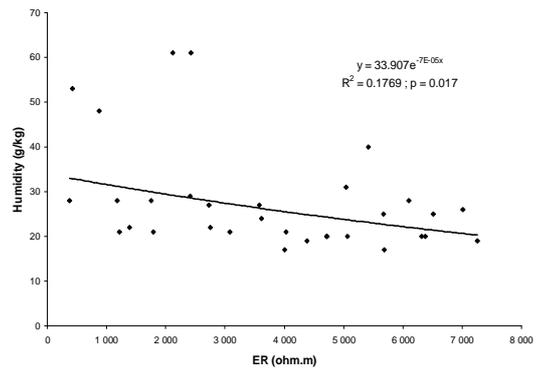
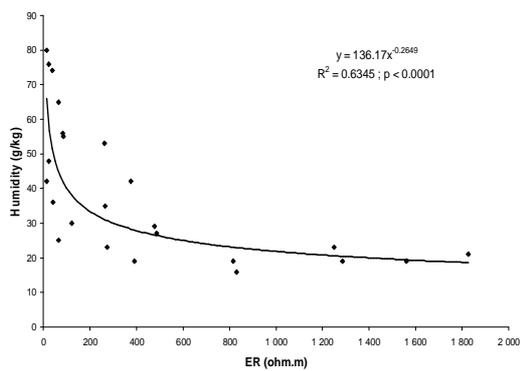
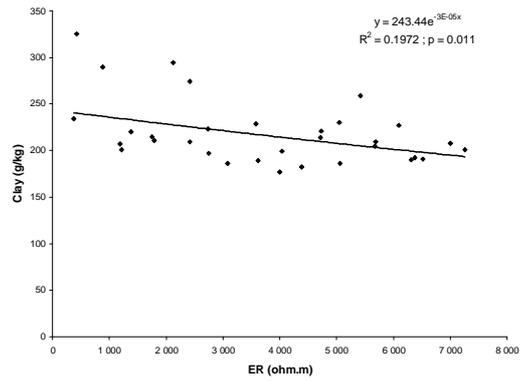
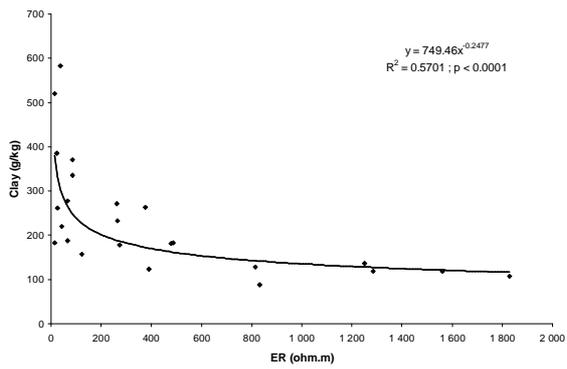
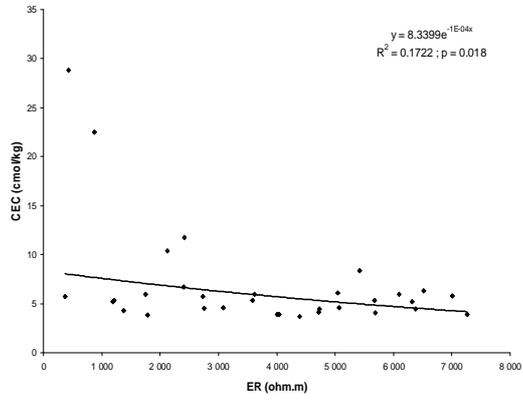
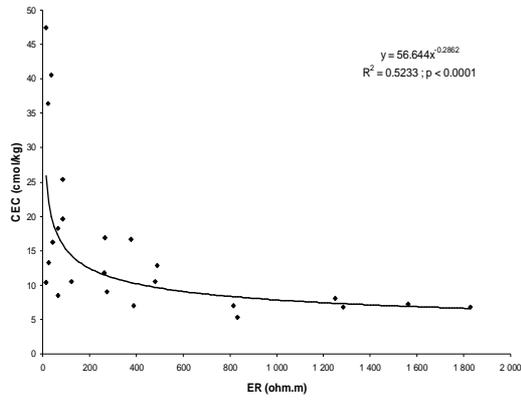


401 Figure 2: Regressions between ER and soil properties (CEC, clay content and humidity). 2a)

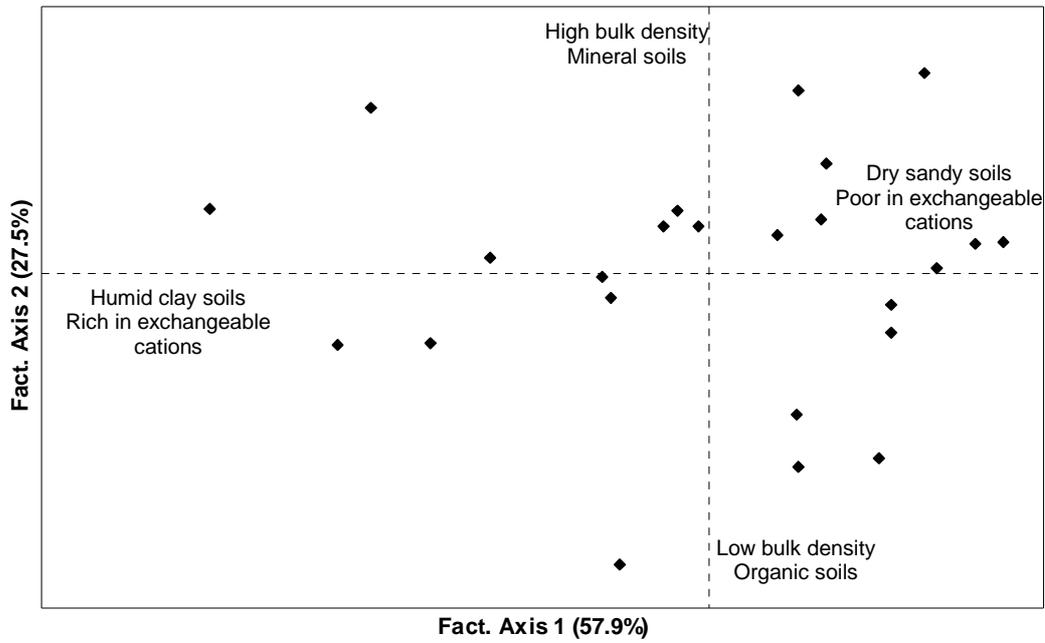
402 EPC74 plot; 2b) CHS01 plot

403 2a) plot EPC74

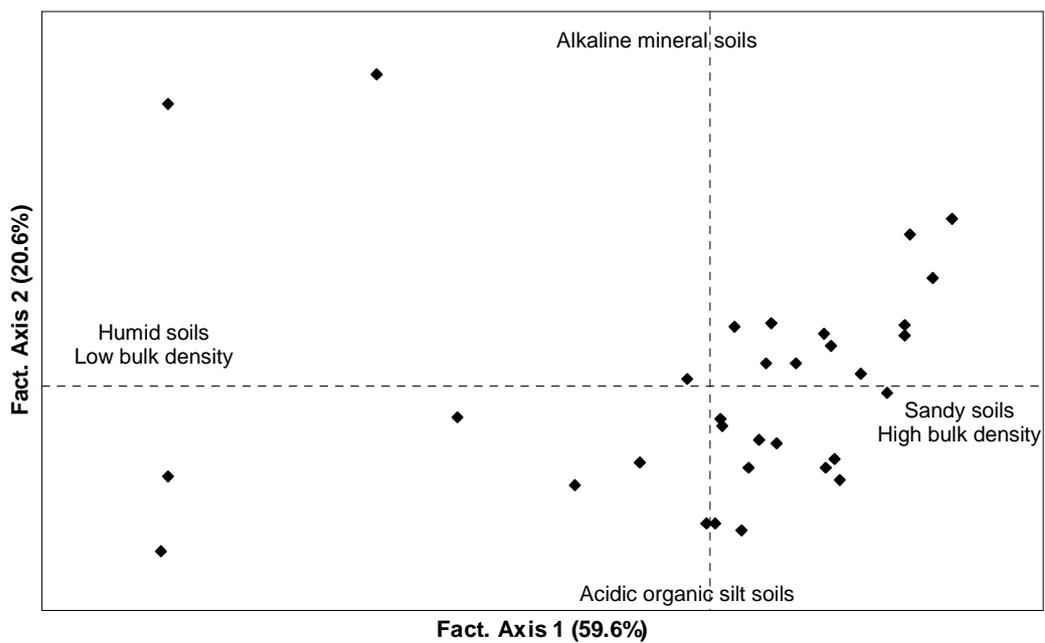
2b) plot CHS01



404 Figure 3: Principal Component Analyses (two-first factorial axes). Soil properties analysed:
 405 CEC, Total N, Organic C, C/N, Clay, Silt and Sand proportions, humidity, pH, dry bulk
 406 density. The PCA was centred and scaled.
 407 3a) plot EPC74



408
 409 3b) plot CHS01



410

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

Soil property	EPC74 (n=24)					CHS01 (n=32)				
	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 (23%)	127.98 (13%)	88.0 (9%)	583.0 (58%)	1.20	218.59 (21.9%)	34.97 (3.5%)	177.0 (17.7%)	325.0 (32.5%)	1.41
Silt (g/kg) (%)	215.17 (22%)	54.09 (5%)	134.0 (13%)	303.0 (30%)	0.03	630.53 (63.1%)	32.50 (3.3%)	548.0 (54.8%)	676.0 (67.6%)	-0.41
Sand (g/kg) (%)	550.88 (55%)	172.35 (17%)	144.0 (14%)	771.0 (77%)	-0.75	150.88 (15.1%)	34.14 (3.4%)	56.0 (5.6%)	216.0 (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

413 Table 2: Determination coefficients (r) between electrical resistivity and soil properties,
 414 regressions and Moran tests for spatial autocorrelation of the residuals results. ER data have
 415 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	
CHS01 (n=32)		r	F_{1,30}	p-value	I	p-value
	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					

^adata has not been log-transformed

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

416