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1 **Mapping spatial distribution of soil properties using electrical resistivity on a long term**  
2 **sugarcane trial in South Africa**

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12

13 **Abstract**

14 In experimental trials the spatial distribution of soil properties is a key factor to evaluate and  
15 determine the credibility of the research outcomes. To evaluate the spatial distribution of soil  
16 properties at different depths in the present study, the electrical resistivity method was  
17 selected because of its non-destructive nature and high spatial resolution.

18 The investigation was conducted on BT1 (Burning versus mulching) the world's oldest  
19 sugarcane trial (established 25 October 1939) located on the premises of the South African  
20 Sugarcane Research Institute (SASRI). The experimental area, covering 7200 m<sup>2</sup>, is divided  
21 in 32 plots with three crop residue retention treatments. These treatments are either fertilized  
22 and not fertilized. The RM15 resistance-meter equipped with a multiplexer was used to  
23 collect geophysical data. The latter was used to generate apparent electrical resistivity maps  
24 corresponding to three approximate depth ranges: (0 - 0.5 m, 0 - 1.0 m and 0 – 2.0 m). The  
25 spatial resolution of the shallowest map (0 - 0.5 m), was 0.5 m x 1.0 m. Bulk density and soil  
26 water content, for the 0 - 0.1 m depths, were also determined from samples collected on a grid  
27 of 4 m x 5 m. All data collected were georeferenced using a spatial resolution of 4 m x 1 m  
28 with the Digital Elevation Model (DEM).

29 The results of this survey showed the effectiveness of geophysical mapping to reveal detailed  
30 information regarding soil spatial variability and to understand and establish the relationships  
31 between soil fertility and soil physical properties. Detailed analysis of these results led to the  
32 identification of two different soil types on the trial site: a Mollic Cambisol in the upper slope  
33 of the trial with a depth of less than 1.0 m and a deeper Mollic Nitisol in the lower slope.  
34 Additionally, close to the southern edge of the site, higher values of electrical resistivity

35 revealed a layer of colluvial deposits, that has not been considered in the past. The  
36 relationships between electrical resistivity and investigated soil properties (soil water content,  
37 bulk density, aggregate stability and fertilizer) initially seemed paradoxical. Although there is  
38 still a need for further investigations, the current study decently establish the rather  
39 unexpected relationships. The most striking finding was the high resistivity in fertilised plots  
40 associated with the application of potassium chloride fertiliser which led to a decreased soil  
41 aggregate stability.

42 **Key words:** electrical resistivity mapping, sugarcane, mulch, fertilizer, bulk density, soil water  
43 content, soil physical properties, long term trial.

44

## 45 **1. Introduction**

46 The current study was conducted in the long-term continuously monitored sugarcane trial  
47 (BT1). This trial commenced in October 25, 1939 at the South African Sugarcane Research  
48 Institute (SASRI) located in Mount Edgecombe (near Durban) to investigate the effect of  
49 greencane harvesting and burning of sugarcane prior to harvest as well as continuous fertiliser  
50 application on soil and cane yields (Van Antwerpen et al., 2001). There are several studies  
51 that have been conducted in this trial to monitor the changes in soil and crop yield (Van  
52 Antwerpen et al., 2001; Graham et al., 2002; Mthimkhulu et al., 2016)..

53 These studies have revealed that burning of sugarcane prior to harvest under the monocultural  
54 system and conventional tillage leads to a decline in soil carbon content (SOC) and soil  
55 fertility. Their findings also showed that greencane harvesting, an alternative to pre-harvest  
56 burning, encourages the retention and mulching of all leafy non-sucrose containing crop  
57 material on the soil surface and potentially increase SOC (Graham et al., 2002). The most  
58 recent investigation by Mthimkhulu et al. (2016) reported a significant increase in acidity and  
59 a decrease in soil aggregate stability and base cations (calcium and magnesium) which was  
60 attributed to mining of nutrients by sugarcane, nitrification and subsequent leaching of base  
61 cations. However, none of these studies conducted a precise soil mapping of the trial to  
62 provide systematic georeferenced information on the spatial distribution of soil physical  
63 characteristics such as depth, texture, bulk density, aggregate stability and soil water  
64 properties that might be influenced by the treatments and topography.

65 Topography is generally one of the major factors in soil formation and its impact is very  
66 important on agricultural fields in terms of soil spatial variability, nutrients concentration and  
67 leaching of chemicals (mineral fertilizers) and, therefore, has a significant influence on the  
68 crop yields (Biggar and Nielsen, 1976; Yang et al., 1998; Iqbal et al., 2005; Senthilkumar et  
69 al., 2009). Terrain relative elevation, shape of the relief, slope gradient, as well as its

70 orientation and its amplitude represent important topographical factors of the soil evolution.  
71 They define the principal properties of hydrological functioning of the arable land, like the  
72 water flux potential and the peculiarities of the runoff erosion, or sediments transport and  
73 deposition (Moore and Burch, 1986; Changere and Lal, 1997; Bakhsh et al., 2000;  
74 Kravchenko and Bullock, 2002). Under certain conditions, these phenomena are considered as  
75 the main cause of the decline in soil quality on a cultivated steep hillslope (Li and Lindstrom,  
76 2001).

77 Generally the annual input of organic matter is expected to have a considerable effect on soil  
78 porosity, soil structure (Blair, 2000) and soil water content as mentioned by Robertson (2003)  
79 but data are scarce. The stability of the aggregates and the connectivity of pores between them  
80 is well known to affect the movement and storage of water, aeration, erosion, biological  
81 activity and the growth of crops (Amezketta, 1999, Boix-Fayos et al., 2001).

82 In order to better our understanding of these soil properties and their response to external  
83 factors such as topography and land management practices precise mapping is required.  
84 Classical approach to mapping soil physical properties is based on data collected at discrete  
85 observation points; detailed mapping thus becomes very costly when a large number of data  
86 points are required. Opening soil profile pits and sampling large volumes of soil are generally  
87 requested for that purpose. However, this *modus operandi* can be very destructive and  
88 impossible in an experimental trial covering a relatively small area, and where intensive soil  
89 disturbance is unwanted. In this context, the use of geophysical methods has been proven to  
90 be efficient and meaningful in the non-intrusive collection of data (Corwin and Lesch, 2003;  
91 Samouëlian et al., 2005). As demonstrated in several studies, geophysical techniques, such as  
92 electrical resistivity mapping, are very well adapted for use on agronomic trial sites (Corwin  
93 and Lesch, 2005; Tabbagh et al., 2000). However an empirical relationship needs to be  
94 established for each site between soil electrical resistivity values and soil physical properties

95 as these relationships may be site-specific (Friedman, 2005). Examples of such relationships  
96 have been published for water content and bulk density (Cousin et al., 2005), waterlogged soil  
97 horizons and spatial-temporal distribution of soil water following irrigation (Michot et al.,  
98 2003; McCucheon et al., 2006). Geophysical methods have also been used to study soil  
99 textural changes with depth, to evaluate soil thickness *i.e.* the depth to the parent rocks  
100 (Milsom, 2003), to locate the presence and to define the thickness of compacted or low  
101 density horizons, and to characterise textural properties in duplex soils (McCarter, 1984). It  
102 has also been found very efficient in assessing soil salinity through increased electrical  
103 conductivity values (Rhoades et al. 1989).

104 To characterize the spatial distribution of the different soil properties in the BT1 experimental  
105 site, we applied the method of electrical resistivity mapping with high spatial resolution,  
106 corresponding to 3 different depths of investigation.

107 The main objectives of this study were: i.) to collect information on soil spatial variability,  
108 soil thickness and pedological changes within the trial, down to approximately 2 m depth; ii.)  
109 to analyse and identify changes in electrical resistivity related to soil characteristics, such as  
110 water content or bulk density; and, iii.) to assess the impact of different treatments (mulch,  
111 fertilization, etc.) on the evolution of soil properties in the experimental plots.

## 112 **2. Material and methods**

### 113 *2.1 Site location, soil properties*

114 The experimental site (BT1) is located on the premises of the South African Sugarcane  
115 Research Institute, at Mount Edgecombe, in KwaZulu-Natal province, South Africa  
116 (31°02'41.10" E ; 29°42'10.82" S). The highest elevation which corresponds to the North-  
117 Eastern corner is 99 m above sea level (a.s.l.), with an average slope of 15% facing South-  
118 West (Fig.1a). The surface of this experimental site has a parallelogram shape, nearly  
119 rectangular, and covers an area of 7200 m<sup>2</sup> (90 m x 80 m) with the following corner

120 coordinates (36J 310840 E, 6712525 N; 36J310805 E, 6712455 N; 36J310730 E, 6712490 N;  
121 36J310765 E, 6712560 N) in the Universal Transverse Mercator (UTM) geographic  
122 coordinates system (Fig.1b).

123 The regional climate is subtropical humid and is characterized by summer (October–March)  
124 rainfall. The average annual precipitation is 950 mm, and the average annual temperature is  
125 20.4°C.

126 The soil was initially classified as Vertisol, (Graham et al. 2002) with a dark (2.5YR 3/1 to  
127 3/2) 50 cm thick A horizon extending to a dark reddish brown (2.5YR 3/3 to 3/4) AC  
128 transitional horizon overlying weathered dolerite. The profile in the upper slope contained a  
129 5 cm thick stone-line at a depth of about 30-40 cm overlying weathered dolerite (Fig.2). On  
130 the lower slope, the soil has the same A horizon as the upper slope, but overlying a red  
131 (2.5YR 3/4 to 10R 3/6) B horizon. The soil texture of the A horizon is generally clayey with a  
132 little over 40 % of clay and less than 20% of sand in the upper 20 cm. Downstream, in the  
133 lower part of the slope, the soil texture becomes clay - loamy with the sand content slightly  
134 above 20%. The clay mineralogy is dominated by kaolinite with some scattered evidences of  
135 smectite. The soil pH in water is ranging between 4.2 and 5.7. More details of the trial and  
136 analytical methods are described by Mthimkhulu et al. (2016).

### 137 *2.2 Experimental design*

138 This experimental site has been described in details by Thompson (1966), Van Antwerpen  
139 and Meyer (1998), and Van Antwerpen et al., (2001). The complete trial is composed of 32  
140 plots divided in 4 columns and 8 rows (Fig.1b). Each plot of 175 m<sup>2</sup> is 18 m long and 9.6 m  
141 wide. In each plot the sugarcane is planted in 7 rows parallel to the plot long edge and spaced  
142 1.37 m. The treatments were: 1) Unburned at harvest with the residue (mainly brown and  
143 green leaves) retained on the soil surface to provide a mulch cover (M); 2) Sugarcane burned  
144 at harvest with the partially unburned green tops scattered evenly over the soil surface (BS);

145 3) Sugarcane burned at harvest with the unburned green tops removed from the soil surface  
146 (BR). These treatments were further subdivided into fertilized (F) and unfertilized plots (F0)  
147 in a split-plot design with eight replications for M and four replications for BS and BR  
148 treatments.

149 Since the trials' inception in October 25, 1939, the soil at the site has been disturbed only  
150 seven times. Initially replanting involved conventional tillage, which imply that the total trial  
151 area was ploughed in preparation for planting. In 1970, minimum tillage was adopted with  
152 disturbance of the planting row only. All fertilized treatments received 140 kg of nitrogen (N)  
153 (as  $(\text{NH})_2 \text{SO}_4$  - ammonium sulphate), 28 kg of phosphorus (P) (as  $\text{P}_2\text{O}_5$  - superphosphate)  
154 and 140kg of K (as KCl – potassium chloride) per hectare, applied as 5:1:5 (46%) at 670 kg  
155  $\text{ha}^{-1}$  approximately 40 days after harvesting (van Antwerpen et al., 2001). There were small  
156 fluctuations of the fertilizer composition during the last 20 years. No compensation is made  
157 for the nutrients recycled through the retention of residue after harvest. Since 1987 the crop is  
158 annually harvested in spring (September) at the beginning of the rainy season.

159 It may be added that the presence of termite nests of *Odontotermes sp.* was evidenced by  
160 vertical chimneys deeper than 0.6 m and with a diameter of 0.15 m at the north of plot 9 and  
161 west of plot 22 (Fig. 1b). In that area, termite nests are generally located on the external  
162 border of sugarcane plot surrounded by grass pathways.

### 163 *2.3 Topographic survey*

164 A high precision topographic map of the study area was created using a laser tacheometer  
165 (LEICA Total Station - TC 302). The use of this equipment made it possible to determine the  
166 horizontal coordinates (X and Y) with errors less than  $\pm 0.10$  m, and the altitude Z, with errors  
167 smaller than  $\pm 0.05$  m.

168 This survey was carried out for two reasons: (i) in order to be able to study the impact of  
169 topography on soil properties at large; (ii) and to define the georeferenced coordinates of each



170 plot and their boundaries with high precision. For the elevation model, the measurements over  
171 the entire site were made at the nodes of a 4 m x 1 m rectangular grid. A 0.5 m mesh digital  
172 elevation model (DEM) was generated using these results, which provides the accuracy and  
173 density of measurement points required. Thanks to this model, all actions and experimental  
174 interventions (positions of different sensors, auger soundings or pedological pits, etc.) could  
175 be now georeferenced.

#### 176 *2.4 Soil water content and bulk density*

177 The soil samples used for the determination of soil water content (SW) and bulk density (BD)  
178 were collected from the whole trial area at the 0–10 cm soil layer, following a 4 m x 5 m grid.  
179 This sampling was made simultaneously with measurements of electrical resistivity. A total of  
180 325 undisturbed soil cores (250 cm<sup>3</sup>) were collected: 275 within the plots and 50 within the  
181 alleys. All the samples were oven dried at 105°C for 24 hours. The final results will be  
182 presented as two maps (SW and BR) where the “Nearest Neighbour” data interpolation  
183 method has been used for both parameters.

#### 184 *2.5 Soil structural stability*

185 The soil structural stability was determined on the soil samples using the fast wetting AFNOR  
186 (2005) method developed by Le Bissonais (1996). The aggregate stability data, calculated  
187 from a nest of six sieves (2, 1, 0.5, 0.2, 0.1 and 0.05 mm), was converted to mean weight  
188 diameter (MWD) according to Kemper and Rosenau (1986). Three replicate soil samples used  
189 to measure this parameter were collected at two depths (0-10 and 10-20 cm, i.e. six samples  
190 per plot) from three mini-pits in each of the thirty-two plots. The total of samples analysed for  
191 MWD was 192.

#### 192 *2.6 Apparent electrical resistivity mapping*

193 Electrical resistivity mapping of the whole trial, including breaks between plots, was carried  
194 out in November 2011, after harvesting that took place in September, but prior to the annual

195 fertilization.

196 For the measurements we used the so called "pole-pole" configuration of electrodes,  
197 consisting of two mobile electrodes (the current electrode and the potential electrode) with the  
198 second pair (current and potential) of electrodes remote and fixed far enough from the  
199 prospecting area, to be considered as an infinite distance. This condition is satisfied if the  
200 remote electrodes are placed at a distance greater than 20 times the spacing between the  
201 mobile electrodes (Robain et al., 1999). The use of the "pole-pole" electrode array is justified  
202 because it reduces the number of mobile electrodes from 4 to 2 for each measurement, and  
203 thus allow high productivity. This electrode configuration is relatively sensitive to non-  
204 horizontal boundaries and heterogeneities and provides greater depths of investigation,  
205 compared to other arrays (Seaton and Burbey, 2002). At the surface of a homogeneous  
206 medium, it measures the so-called "true resistivity" of the medium ( $\rho$ ) (expressed in Ohm·m  
207 or  $\Omega\cdot m$ ). It integrates a volume of medium roughly hemispheric around the 2 mobile  
208 electrodes, *i.e.* down to a depth roughly equal to the electrode spacing (Oldenburg and Li,  
209 1999). At the surface of a non-homogeneous environment, in the case of our survey for  
210 instance, the equipotential surfaces around the current electrode are no more hemispheric;  
211 their actual geometry depends on the different media around the electrodes; it measures a so-  
212 called "apparent resistivity" ( $\rho_a$ ) (expressed also in Ohm·m or  $\Omega\cdot m$ ), related to the true  
213 resistivities of the surrounding media. Practical experience and numerical modelling however  
214 have proven that: (i) the greater the separation between the two electrodes, the greater the  
215 depth of exploration and (ii) apparent resistivity maps can be interpreted qualitatively and  
216 provide very useful information on the study site. Inversion procedures to transform apparent  
217 resistivities into 2 or 3 dimensional models with "true resistivities", so-called "electrical  
218 tomographies", require much heavier and costly field operations, which are performed only  
219 when detailed investigations and modelling are mandatory.

220 The measurements were performed using a "Resistance Meter RM-15" equipped with a  
221 "MPX15 multiplexer" and connected to a "PA20 multi-probe array" (Geoscan Research,  
222 Heather Brae, Chrisharben Park, Clayton, Bradford, West Yorkshire BD14 6AE, UK).

223 To simplify the transportability of the instrument by a single operator from one point of  
224 measurement to the next, the resistance-meter and the multiplexer are fixed on a versatile  
225 frame whose basis is a beam with a length of 2 m, on which 5 stainless steel electrodes are  
226 mounted with a spacing  $a = 0.5$  m. During mapping, the measurements were carried out  
227 moving the device forward with 1 m intervals along lines perpendicular to the northern edge,  
228 and with 2 m spacing between successive lines. Seven readings were recorded at each  
229 position of the device: 4 measurements with an electrode spacing of 0.5 m ( $a = 0.5$  m); two  
230 measurements with electrode spacing of 1.0 m ( $a = 1.0$  m) and one measurement with  
231 electrode spacing of 2.0 m ( $a = 2.0$  m). The number of measurements obtained with a  
232 0.5 m x 1.0 m 1.0 m x 1.0 m, and 2.0 m x 1.0 m grid spacing were 13600; 6800 and 3400 data  
233 points respectively. We were thus able to draw and present three "apparent resistivity" maps  
234 representative of three soil thicknesses, approximately 0 - 0.5 m, 0 - 1 m and 0 - 2 m.

235 These maps were analysed by comparison with the topographic features, water content, bulk  
236 density, and aggregate stability characteristics, at the relevant depths (0 - 10 cm and 10 -  
237 20 cm).

### 238 **3. Results**

#### 239 *3.1 Topographic survey*

240 From our topographic survey, as mentioned above (§2.3), a 0.5 m mesh Digital Elevation  
241 Model (DEM) was generated. This model was used to determine slope gradients and other  
242 specific relief features were determined, as shown on Fig. 3. The highest absolute elevation  
243 was equal to 99 m a.s.l., while the lowest was 85 m a.s.l., isohypses every 0.5 m altitude  
244 difference, magnitude and azimuth of slope gradients as shown by vectors.

245 The surface of the trial is mainly facing southwest with the axis of the general slope  
246 coinciding approximately with the NE-SW diagonal. The average slope along this axis is  
247 12 %, but it is not constant. It represents a convex then concave shape, with an average slope  
248 of 10-12 % close to the upper northeast corner; in the central part of the trial, the slope  
249 increases to 15-17 %, and then declines to 4-8 % at about 15-20 meters, near the southwest  
250 corner. The difference in altitude is larger at the eastern (10.5m) and northern edges (9.2 m),  
251 compared to the western (4.6 m) and southern edges (3.2 m). In addition, these slopes are  
252 neither uniform nor linear. So, it should however be noted that the topographic surface of the  
253 trial is rather complex and this can have major impacts on the soil properties.

254 On the map (Fig.3), the arrows indicate the energy and direction of the rainwater flows. They  
255 exhibit rather large differences in magnitude and azimuths: the flow direction is a)  
256 approximately perpendicular to the sugarcane rows in the eastern part of the site, b), it crosses  
257 the rows with an angle close to 45° in the central and south-western parts, and c) it is  
258 practically parallel to the rows in the north-western part. These important differences in  
259 intensity and direction of the water flows are major features of the trial site because of their  
260 substantial influence on the erosion and dissolution phenomena, as well as on the transport  
261 and deposition of solutes and suspended particles.

### 262 *3.2 Soil water content and bulk density*

263 The main SW results are shown on Fig. 4a and 4b. The points in Fig.4a indicate the positions  
264 where soil samples used for SW and the BD (bulk density) values were collected. The map of  
265 SW determined at 0-10 cm, indicated that this property is affected by crop residues retention  
266 treatment (i.e. M treatments show high values of SW).

267 The SW increased with increase in crop residues on the soil surface in fertilized and  
268 unfertilized treatments as anticipated ( $0.36 \text{ kg}\cdot\text{kg}^{-1}$  for (MF) plots  $> \text{BSF}$  ( $0.24 \text{ kg}\cdot\text{kg}^{-1}$ )  $> \text{BRF}$   
269 ( $0.19 \text{ kg}\cdot\text{kg}^{-1}$ ) and MF0 ( $0.32 \text{ kg}\cdot\text{kg}^{-1}$ )  $> \text{BSF0}$  ( $0.25 \text{ kg}\cdot\text{kg}^{-1}$ )  $> \text{BRF0}$  ( $0.20 \text{ kg}\cdot\text{kg}^{-1}$ ) (Fig. 4b).

270 The SW median values in MF treatment ( $0.36 \text{ kg}\cdot\text{kg}^{-1}$ ) are slightly higher compared to the  
271 MF0 treatment ( $0.32 \text{ kg}\cdot\text{kg}^{-1}$ ), and this could be attributed to the larger amount of residue  
272 material resulting from the combination of fertilizer and crop residues. The SW differences  
273 are observed between the fertilized and unfertilized plots were not significant for BS and BR  
274 treatments. Concerning the dispersion, *i.e.* the distance between the two extreme quartiles, it  
275 is rather small for BR and BS and greater at the M treatment.

276 Similarly to the SW map, with the soil bulk density (BD) map, all the M treatments were easy  
277 to identify (Fig.5a), The highest and the lowest bulk densities were measured at BR  
278 ( $1.18 \text{ g}\cdot\text{cm}^{-3}$ ) and M treatments ( $0.82 \text{ g}\cdot\text{cm}^{-3}$ ) respectively. The same statistical approach as  
279 above has been applied to each six populations (Fig.5b). The general trend showed a decrease  
280 in BD from  $1.13 \text{ g}\cdot\text{cm}^{-3}$  at BRF0 to  $1.0 \text{ g}\cdot\text{cm}^{-3}$  at the MF. Fertilized plots had lower BD values  
281 across all the crop residue treatments compared to F0. Besides the measurements are  
282 characterized by relatively high interquartile dispersions, indicating large heterogeneities in  
283 the density the investigated soil.

### 284 3.3 Soil structural stability (MWD)

285 The MWD are presented in Fig.6a and 6b, These results indicated that the MWD does not  
286 vary much relative to the residue treatments, but it decreased significantly in the F plots in  
287 both mulched and burnt treatments. The MWD in F0 ranged from 1.72 mm (BSF0) to  
288 2.33 mm (BRF0) at 0 – 10 cm depths, and from 2.22 mm (MF0) to 2.41 mm (BRF0) at 10 –  
289 20 cm depths.

290 It was also worth noting that MWD were slightly higher at 10 – 20 cm depths of F treatment,  
291 the median values ranging from 1.50 mm for MF to 1.75 mm for BRF, and from 1.11 mm for  
292 BRF to 1.37 mm for MF. at 0 – 10 cm depths. An increase in MWD (from 1.11 in BRF to  
293 1.37 mm in MF) attributed to increase in crop residues was only observed at 0 – 10 cm of the  
294 F treatment. At 10 – 20 cm depths, it decreased, from 1.75 mm to 1.50 mm.

295 The results also show that the fertilizer application leads to a nearly identical light decrease in  
296 MWD values, from 0.6 mm to 0.8 mm, for all types of treatments at both depths, except for  
297 the difference between (BRF0) and (BRF) at 0 – 10 cm depths, where it is quite large  
298 (1.22mm), representing a variation greater than 50%.

### 299 *3.4 Soil electrical resistivity mapping*

300 Three apparent electrical resistivity ( $\rho_a$ ) maps are shown on Fig.7 a, b and c, corresponding to  
301 three increasing thicknesses, as explained above, since they represent the results of  
302 measurements with increasing electrode spacing **a**, from 0.5 m to 1.0 m and to 2.0 m.

303 The map representing the measurements with electrode spacing **a** = 0.5 m (Fig.7a) should be  
304 the most sensitive to the soil properties, since it corresponds to the shallowest depth of  
305 investigation. In the central part of this map, a band of low resistivity values (roughly  
306  $\rho_a \leq 20 \text{ Ohm}\cdot\text{m}$ ) is observed, extending from the north-western to the south-eastern corner.

307 The boundaries of this zone are almost parallel to the topography.

308 Within this area the seven plots that seem to be more conductive than others include:  
309 1 (BSF0), 2 (BRF), 4 (BRF0), 11 (MF0), 13 (BRF0), 20 (MF0) and 32 (MF0); It is worth  
310 noting that about 85% of these samples are F0 and that there were only three plots in the F  
311 treatments that showed slightly more resistivity, namely; 3 (BSF), 12 (MF) and 22 (BSF).  
312 Moreover, the highest values of apparent resistivity ( $\rho_a > 25 \text{ Ohm}\cdot\text{m}$ ) were found in the  
313 northeast of the central conductive area. Three out of the four southern plots show relatively  
314 high resistivity values, around 30 – 35  $\text{Ohm}\cdot\text{m}$ .

315 The map corresponding to **a** = 1.0 m (Fig. 7b), the intermediate thicknesses, shows a similar  
316 pattern as Fig. 7a. The central conductive strip appears sharper and more homogeneous,  
317 especially to the west. The north-eastern resistive area looks also more homogeneous and its  
318 southern boundary follows isohypses very well. Compared to the previous map, the southern  
319 resistive area is reduced in intensity and dimensions.

320 The third map ( $a = 2$  m) (Fig. 7c), with the greatest depth of investigation, shows a regular  
321 gradient from the northeast to the southwest, following the isohypses. The resistivity values  
322 decrease from about 40 Ohm·m down to approximately 15 Ohm·m.

323 It is important to note that as soon as these 3 maps were available, *i.e.* during the survey, 17  
324 points were selected from the entire surface of the BT 1 trial, where auger drillings were  
325 performed to establish the relationship between the electrical resistivity distribution and  
326 various soil properties, such as its nature, thickness, texture, soil aggregate stability, SW and  
327 BD.

328 These 3 maps definitely allowed us to characterize the spatial variability of the soil properties  
329 of the trial. First, these results have assisted in the reclassification of soils of the trial and also  
330 formed basis of the further studies. For instance, this this trial was believed to have one soil  
331 type known as Vertisol. However, the current study showed there are two soils in this trial  
332 which are: Mollic Cambisol to the Northeast and Mollic Nitisol to the South- and Southwest  
333 (Mthimkhulu et al., 2016).

#### 334 **4. Discussion**

335 The outcomes of the electrical resistivity mapping of the trial provided four types of  
336 information: (i) variation of the soil thickness in relation to topography, which further led to  
337 the with two different soil types separated by altitude; ii) Existence of a soil thin layer of  
338 colluvium origin, located in the lower part of the trial; iii) Land management influence on soil  
339 properties.

##### 340 *i.) Soil thickness*

341 The electrical resistivity ( $\rho_a$ ) map with the greater depth of investigation (Fig. 7c) shows a  
342 high resistivity anomaly in the North-East part, and good correlation with topography. It is  
343 enhanced on Fig.8b obtained through low pass filtering of the raw map ( $a=2$ m). These results  
344 could be due to the closeness of soil surface to the parent rock as a result of shallow depth (<

345 1 m). The depth of the parent rock was confirmed soil auguring, which additionally led to the  
346 reclassification of the soil trial. The soil of the entire trial was initially classified as a Vertisol.  
347 For this upper part of trial, it is now re-classified as a Mollic Cambisol (IUSS Working Group  
348 WRB, 2014), with a thick well-structured dark AB horizon, directly laying on the weathered  
349 dolerite. The deep soil in the South and South Western parts of trial is now classified as a  
350 Mollic Nitisol with a dark reddish B horizon (Mthimkhulu et al., 2016). The limit between the  
351 two soil types, after Mthimkhulu et al. (2016), is shown on the map (Fig. 8b); it could be  
352 better ascertained through additional soundings. It should also be noted that in plots 27 and  
353 28, dolerite stones are visible on the surface, and the thickness of the soil does not exceed  
354 0.5 m.

355 *ii.) Superficial colluvial layer*

356 The electrical resistivity map with (a=0.5 m) the shallowest depth of investigation (Fig. 7a)  
357 shows a high resistivity anomaly to the South-West of the trial, which gradually decreases its  
358 intensity and extension on the other two maps (Fig. 7b and c) with deeper depths of  
359 investigation. It has been proven through augering the soundings and by further physical  
360 analysis of the samples that it is due to the presence of a colluvial layer, with higher sand  
361 content (Mthimkhulu et al., 2016). Downstream, where the soil has clay loam texture, the  
362 sand content is slightly over 20 % only in plots 8 (MF), 16 (BSF0) and 24 (BRF), and this  
363 fraction is less than 20% in all other plots. This is also confirmed by the higher BD values on  
364 the same plots 8, 16 and 24. The existence of colluvial deposits had never been detected prior  
365 to electrical resistivity mapping. It appears to be, as a matter of fact, directly related to the  
366 features of the relief.

367 *Land-management effects on electric resistivity*

368 The two maps (SW) and (BD) maps (Fig. 4a and Fig. 5a) showed a clear response to residue  
369 treatments: i.e. higher water content and lower bulk density in the M plots, versus lower water



370 content and higher bulk density in the BR plots and intermediate values in the BS plots. From  
371 classical scientific literature and our experience, we expected a clear and robust relationship  
372 between SW and the electrical resistivity, especially on the map corresponding to the  
373 shallowest depth of investigation (Fig. 7a). This anticipation emanated from that SW has a  
374 sensitivity to the changes that occur in other soil properties and land management practices.  
375 This map, as mentioned above, appears to be strongly influenced by the resistive anomalies  
376 related to the thickness of soil and the colluvial layer although, and no obvious consistency  
377 appears with the water content at first glance. Thorough analyses of Figure 7a showed that  
378 virtually all fertilized plots, except for plot 2, are fully or partially characterized by relatively  
379 higher electrical resistivity values compared to the unfertilized treatments. This appears as a  
380 major paradox: high electrical resistivity values are observed in the plots with higher water  
381 content and, furthermore, these plots have received an additional mineralization.  
382 The relationship between electrical resistivity and soil properties in this trial appears to be  
383 more complex than expected. Would that be a general rule in soil sciences?  
384 According to Archie's law,, electrical resistivity of porous consolidated media decreases with  
385 increasing SW and mineralisation (Glover et al., 2000). Some results concerning soil studies  
386 tend to prove that a somewhat similar law may apply (Michot et al., 2003, McCucheon et al.  
387 2006). According to Cousin et al., (2005) however, the relationship between the electrical  
388 resistivity and water content is not so simple, as they showed that electrical resistivity  
389 decreases with increase in BD. This may partly of the reasons for the observed high electrical  
390 resistivity values in fertilized plots accompanied by a decrease of BD in the current study.  
391 These observations could be due to chemical reactions occurring in the soil.. On the one hand,  
392 fertilizers application increases the concentration of ions in the soil which results raises the  
393 electrical conductivity of the soil, especially in plots regularly fertilized with potassium  
394 chloride (KCl) (Rhoades et al., 1999). On the other hand, changes in the chemical

395 composition and ion concentration of the soil affect its equilibrium and may lead to  
396 physicochemical interactions influencing soil aggregation, namely the degradation of soil  
397 structural stability.

398 In a recent publication Paradelo et al. (2013) reported a severe clay dispersion resulting from  
399 the application of different forms of KCl and soil acidification (with however no dispersion)  
400 where  $\text{NH}_4^{4+}$  was applied in a 48 experimental plots located in Versailles. The dispersive  
401 effect of  $\text{K}^+$  on clays was confirmed by several studies conducted by Marchuk and  
402 Rengasamy (2012). In contrast, the study of Van Antwerpen and Meyer (1998) conducted at  
403 BT1 trial concluded that  $\text{K}^+$  did not cause dispersion due to the release of Al under the low pH  
404 conditions. From the same experimental site, Graham et al. (2002) noticed a slight increase in  
405 both exchangeable and non-exchangeable  $\text{K}^+$  content in the mulched treatment. The major  
406 difference recently measured (at BT1) between the different treatments was the significant  
407 decrease of divalent exchangeable cations  $\text{Ca}^{++}$  and  $\text{Mg}^{++}$  in fertilized plots concomitant with  
408 a decrease of pH (Mthimkhulu et al., 2016).

409 For these last three studies mentioned above, conducted at different years on the BT1 trial, the  
410 samples were collected between January and March, which is the time coinciding with the  
411 sugarcane growth period. Ion concentrations measured on soil samples collected from the  
412 fertilized plots can be relatively higher compared to those in November when electrical  
413 resistivity mapping was performed, since nutrients are continuously extracted until the crop is  
414 harvested in September or October.

415 It could also be assumed that fertilizers can be dissolved and leached by rain, since the rainy  
416 season begins around August, with a monthly average of 70 mm, reaching its maximum of  
417 approximately 120mm in November.

418 With these observations it could be deduced that the high electrical resistivity values  
419 systematically observed in the fertilized plots with chemical inputs (Fig. 6a and b) are due to

420 the soil structural stability degradation, related to complex physicochemical interactions. This  
421 deduction is also in agreement with the influence of the so-called pore tortuosity. The  
422 tortuosity factor is known to be important in contributing to high resistivity in porous media  
423 (Kunetz, 1966). While this factor was well documented for rocks and reconstructed porous  
424 media, it is not yet considered for soils and inter-aggregate porosity.

425 To conclude, we believe that a better understanding of the origin of these high electrical  
426 resistivity values in the fertilized plots, requires additional experimental and theoretical work.

#### 427 *The presence of termite nests*

428 The termites of the *Odontotermes sp.* specie are a fungus-culturing termites, making comb  
429 nest chambers with large void space that could generate high values of local electric  
430 resistivity (Fig. 7a). However, the decrease in the resolution of the measurement with depth  
431 make it difficult to separate resistivity features of termite nests from other sources, resulting  
432 in high resistivity.

#### 433 **Conclusion**

434 The results of electrical resistivity mapping of the investigated trial showed strong lateral  
435 variations associated to the soil thickness, soil texture and other soil properties. The main  
436 findings were as follows: i) Soil depth increased from North East to the South West of the  
437 trial , but this had no effect the on topsoil characteristics (0-20 cm). This study revealed that  
438 the trial was established on two different soils including Cambisol (upper slope) and Nitisol  
439 (lower slope) although previous studies have reported a single soil type (Vertisol) in this trial;  
440 ii) The increase in soil resistivity and depth in the SW corner of the trial was attributed to  
441 accumulation of colluvium material; it may now be considered as a possible hidden limiting  
442 factor for sugar cane growth apart from the sole treatment effect, and be included in further  
443 investigations of yield variability ; iii). The soil resistivity in the soil surface showed no clear  
444 relationship with SW content or bulk density (mulch effect) and this was found to be very

445 strange as SW was significantly higher in the topsoil of M plots; iv). The topsoil resistivity  
446 showed some relationship with fertilizer treatments such that higher electrical resistivity  
447 observed in fertilized plots was associated with lower soil structural stability measured in the  
448 treatment. However the electric resistivity was not related to the inputs of salts (KCl) as  
449 fertilizers; v) The termite nests are identified to be more resistant but no correlation with  
450 resistant points and termite nests could be established.

451 The results of the soil electrical resistivity mapping showed that the effect of long term use of  
452 fertilizers deeply affects the porous media and soil physical properties, while mulching only  
453 temporarily affects the soil surface water content and bulk density, with limited effects on the  
454 soil structural and chemical properties at depth.

455 Geophysical mapping appear as time-consuming and as a relatively heavy operation, but the  
456 information it provides makes it largely beneficial, from a methodological, as well as from a  
457 practical point of view. However, having reported that, further experimental and theoretical  
458 works are still needed to better understand the relationship between electrical resistivity and  
459 all classical pedological parameters. The current experimental survey provided an  
460 instantaneous pictorial representation of soil variability that was required for the better  
461 understanding of the interaction of factors and processes leading to the evolution of this long-  
462 term trial.

463

464 References

- 465 AFNOR NF X31-515., 2005. Mesure de la stabilité d'agrégats de sols pour l'évaluation de la  
466 sensibilité à la battance et à l'érosion hydrique, AFNOR, Paris, mars 2005. 13p.
- 467 Amezketa, E., 1999. Soil aggregate stability: a review. *J. of Sustainable Agric.* 14, 83-151.
- 468 Bakhsh, A., Colvin, T.S., Jaynes, D.B., Kanwar R.S., Tim U.S., 2000. Using soil attributes  
469 and GIS for interpretation of spatial variability in yield. *Trans. ASAE* 43, 819–828.
- 470 Biggar, J. W., Nielsen, D. R., 1976. Spatial Variability of the Leaching Characteristics of a  
471 Field Soil. *Water Resour. Res.* 12, 78-84.
- 472 Blair, N., 2000. "Impact of cultivation and sugar-cane green trash management on carbon  
473 fractions and aggregate stability for a Chromic Luvisol in Queensland, Australia." *Soil &*  
474 *Till. Res.* 55, 183-191.
- 475 Boix-Fayos, C., Calvo-Cases, A., Imeson, A.C., 2001. Influence of soil properties on the  
476 aggregation of some Mediterranean soils and the use of aggregate size and stability as  
477 land degradation indicators. *Catena.* 44, 47-67. DOI: 10.1016/S0341-8162(00)00176-4
- 478 Changere, A., and Lal. R., 1997. Slope position and erosional effects on soil properties and  
479 corn production on a Mianian soil in central Ohio. *J. Sustain. Agric.* 11, 5–21.
- 480 Corwin, D.L., Lesch, S.M., 2003. Application of soil electrical conductivity to precision  
481 agriculture: theory, principles, and guidelines. *Agron. J.* 95, 455–471.
- 482 Corwin, D.L., Lesch, S.M., 2005. Apparent soil electrical conductivity measurements in  
483 agriculture. *Comput. Electron Agr.* 46, 11–43
- 484 Cousin, I., Besson, A., Aboubacar Sani, A., Accart, V., Samouëlian, A., Cornu, S., Richard,  
485 G., 2005. Influence of soil water content, soil bulk density, soil solution composition on  
486 electrical resistivity measurements. *EGU 05 Geophys. Res. Abstracts* 7, 08150.
- 487 Friedman, S.P., 2005. Soil properties influencing apparent electrical conductivity: A review.  
488 *Comput. Electron. Agric.* 46, 45 – 70.

489 Glover, P.W.J., Hole, P. J., Pous, J., 2000. A modified Archie's law for two conducting  
490 phases. *Earth Plan. Sci. Let.* 180 (3 \_ 4), 369 – 383.

491 Graham, M.H., Haynes, R.J., Van Antwerpen, R., 2002. Size and activity of the soil microbial  
492 biomass in the row and interrow of a sugarcane field under burning and green cane  
493 harvesting. *Proc. S. Afr. Sug. Technol. Assoc.* 76, 186-195.

494 Iqbal, J., Read, J. J., Thomasson, A. J., Jenkins J. N., 2005. Relationships between Soil–  
495 Landscape and Dryland Cotton Lint Yield. *Soil Sci. Soc. Am. J.* 69, 872–882.

496 IUSS Working Group WRB., 2014. World Reference Base for Soil Resources 2014.  
497 International soil classification system for naming soils and creating legends for soil  
498 maps. *World Soil Resources Reports No. 106.* FAO, Rome.

499 Kemper, W.D., Rosenau, R.C., 1986. Aggregate stability and size distribution. In: A. Klute  
500 (Ed.), *Methods of Soil Analysis: Part 1, Physical and Mineralogical Methods*, 2nd  
501 *Agronomy Monograph No 9, Book Series 5*, Soil Sci. Soc. of Am., Madison, WI, 425–  
502 442.

503 Kravchenko, A.N., Bulloc, D.G., 2002. Spatial variability of soybean quality data as a  
504 function of field topography: I. Spatial data analysis. *Crop Sci.* 42, 804 – 815.

505 Kunetz, G., 1966. *Principles of direct current resistivity processing.* Gebruder Borntraeger.

506 Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil erodibility: I. Theory and  
507 methodology. *Eur. J. Soil Sci.* 47, 425-437.

508 Li, Y., Lindstrom, M.J., 2001. Evaluating soil quality–soil redistribution relationship on  
509 terraces and steep hillslope. *Soil Sci. Soc. Am. J.* 65, 1500–1508.

510 Marchuk, A., Rengasamy, P., 2012. Threshold electrolyte concentration and dispersive  
511 potential in relation to CROSS in dispersive soils. *Soil Res.* 50(6), 473-481.  
512 <http://dx.doi.org/10.1071/SR12135>

513 McCarter, W.J., 1984. The electrical resistivity characteristics of compacted clays.

514 Géotechnique. 34, 263–267.

515 McCutcheon, M.C., Farahani, H.J., Stednick, J.D., Buchleiter, G.W., Green, T.R., 2006.

516 Effect of soil water on apparent soil electrical conductivity and texture relationships in a

517 dryland field. *Biosyst. Eng.* 94, 19–32.

518 Michot, D., Benderitter, Y., Dorigny, A., Nicoullaud, B., King, D., Tabbagh, A., 2003. Spatial

519 and temporal monitoring of soil water content with an irrigated corn crop cover using

520 electrical resistivity tomography. *Water Resour. Res.* 39, 11-38.

521 Milsom J., 2003. *Field Geophysics*. 3<sup>rd</sup> Edition, John Wiley & Sons, New York, 244.

522 Moore, I.D., Burch, G.J., 1986. Physical basis of length-slope factor in the universal soil loss

523 equation. *Soil Sci. Soc. Am. J.* 50:1294 – 1298.

524 Mthimkhulu, S., Podwojewski, P., Hughes, J., Titshall, L., Van Antwerpen, R., 2016. The

525 effect of 72 years of sugarcane residues and fertilizer management on soil physico-

526 chemical properties. *Agric. Ecosyst. Environ.* 225, 54-61.

527 Mualem, Y., Friedman, S., 1991. Theoretical prediction of electrical conductivity in saturated

528 and unsaturated soil. *Water Resour. Res.* 27, 2771–2777. DOI: 10.1029/91WR01095.

529 Oldenburg, D.W., Li, Y., 1999. Estimating depth of investigation in DC resistivity and IP

530 surveys. *Geophysics*. 64 (2), 403–416.

531 Paradelo, R., van Oort, F., Chenu, C., 2013. Water-dispersible clay in bare fallow soils after

532 80 years of continuous fertilizer addition *Geoderma*. 200-201, 40-44.

533 Rhoades, J.D., Manteghi, N.A., Shouse, P.J., Alves, W.J., 1989. Soil electrical conductivity

534 and soil salinity: new formulations and calibrations. *Soil Sci. Soc. Am. J.* 53, 433–439.

535 Rhoades, J. D., Chanduvi, F., Lesch, S., 1999. Soil salinity assessment: Methods and

536 interpretation of electrical conductivity measurements. *Irrigation and drainage paper*,

537 N° 57, 165. FAO, Rome.

538 Robain, H., Albouy, Y., Dabas, M., Descloitres, M., Camerlynck, Ch., Mechler, P., Tabbagh,

539 A., 1999. The location of infinite electrodes in pole – pole electrical surveys:  
540 consequences for 2D imaging. *J Appl. Geophys.* 41, 313 – 333.

541 Robertson, F., 2003. Sugarcane Trash Management: Consequences for Soil Carbon and  
542 Nitrogen – Final Report of the Project Nutrient Cycling in Relation to Trash  
543 Management. CRC Sugar Technical Publication. CRC for Sustainable Sugar Production,  
544 Townsville.

545 Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., Richard, G., 2005. Electrical resistivity  
546 survey in soil science: a review. *Soil Till. Res.* 83, 173-193.

547 Seaton, W., Burbey, T.J., 2002. Evaluation of two-dimensional resistivity methods in a  
548 fractured crystalline-rock terrane. *J. Appl Geophys.* 51 (1), 21–41.

549 Senthilkumar, S., Kravchenko, A.N., Robertson, G.P., 2009. Topography influences  
550 management system effects on total soil carbon and nitrogen. *Soil Sci. Soc. of Am. J.* 73,  
551 2059–2067.

552 Tabbagh, A., Dabas, M., Hesse, A., Panissod C., 2000. Soil resistivity: a non-invasive tool to  
553 map soil structure horizonation. *Geoderma* 97, 393–404.

554 Thompson, G.D., 1966. The production of trash and its effect as a mulch on the soil and on  
555 sugarcane nutrition. *Proc. S. Afr. Sug. Technol. Assoc.* 40, 333-342.

556 Van Antwerpen, R., Meyer, J.H., 1998. Soil degradation II: Effects of trash and inorganic  
557 fertilizer on soil strength. *Proc. S. Afr. Sug. Technol. Assoc.* 72, 152-158.

558 Van Antwerpen, R., Meyer, J.H., Turner, P.E.T., 2001. The effects of cane trash on yield and  
559 nutrition from the long-term field trial at Mount Edgecombe. *Proc. S. Afr. Sug. Technol.*  
560 *Assoc.* 75, 235–241.

561 Yang, C., Peterson, C.L. Shropshire, G.J., Ottawa T., 1998. Spatial variability of field  
562 topography and wheat yield in the Palouse region of the Pacific Northwest. *Trans. ASAE.*  
563 41, 17–27.

564



565 **Captions and figures**

566 Figure 1a. An aerial view of BT1 trial, with reference to geographical coordinates.

567 Figure 1b. Schematic view of the experimental site BT 1: 32 plots, 3 types of treatments (BR,

568 BS and M), split between fertilized (F) and unfertilized (F0).

569 Figure 2. Profile of a Mollic Cambisol located 10 m East of plot 27.

570 Figure 3. Topographic map and slope gradient vectors: 0.5 m isohypse intervals.

571 Figure 4a. Map of Soil Water Content (SW), overlaid to topography and to the positions of

572 the collected and analysed samples

573 Figure 4b. Results of SW measurements with box and whiskers,

574 Figure 5a. Map of Bulk Density (BD), overlaid to topography.

575 Figure 5b. Results of BD analysis

576 Figure 6a. Results of Mean Weight Diameter (MWD), expressed in mm, for the samples

577 collected in the 0 – 10 cm depth range.

578 Figure 6b. Results of statistical analysis of Mean Weight Diameter (MWD), expressed in mm,

579 for the samples collected in the 10 – 20 cm depth range.

580 Figure 7a. Electrical apparent resistivity ( $\rho_a$ ) map, expressed in Ohm·m ( $\Omega\cdot m$ ) for electrode

581 separation  $a = 0.5$  m.

582 Figure 7b. Electrical apparent resistivity ( $\rho_a$ ) map, expressed in Ohm·m ( $\Omega\cdot m$ ) for electrode

583 separation  $a = 1$  m.

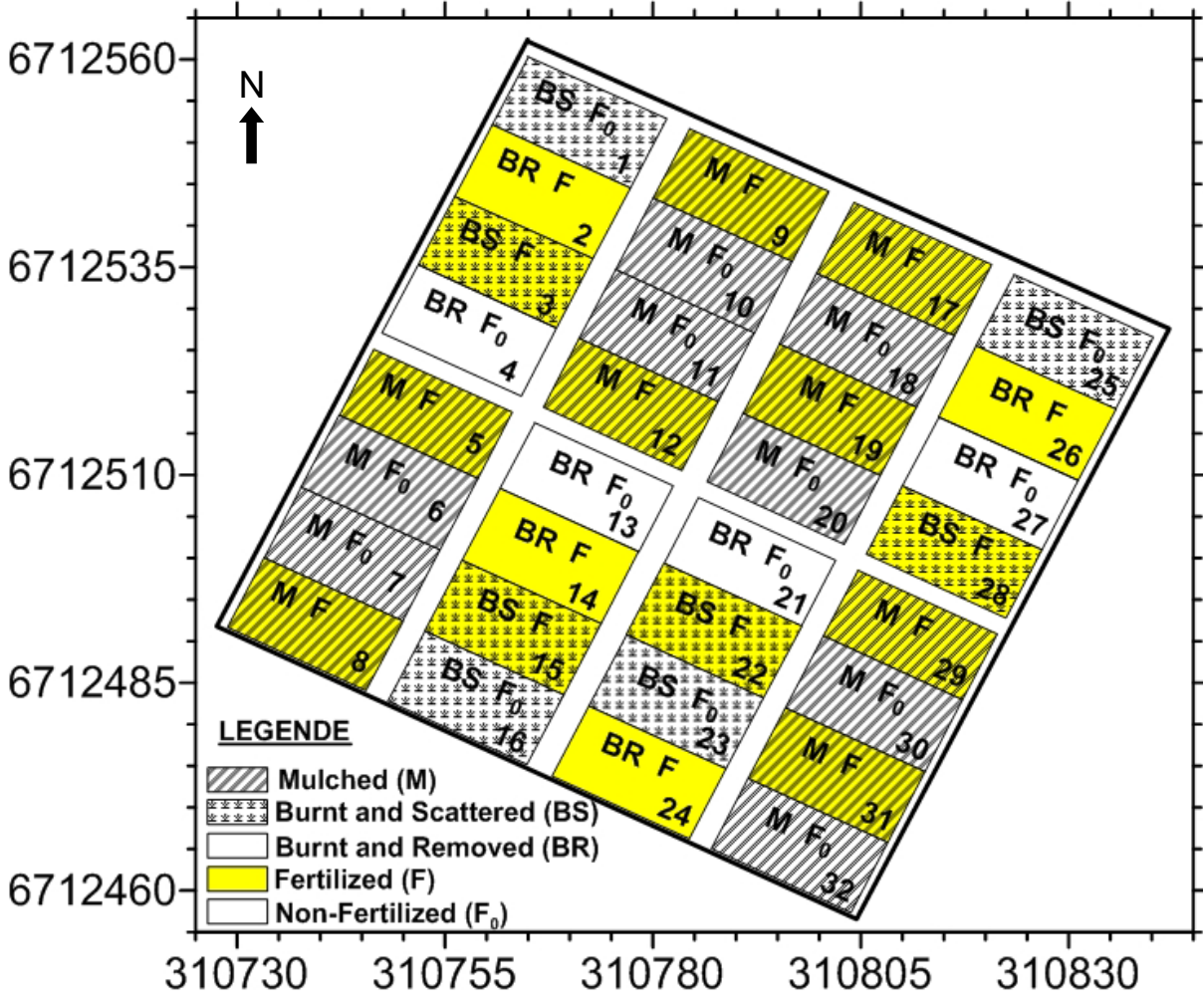
584 Figure 7c. Electrical apparent resistivity ( $\rho_a$ ) map, expressed in Ohm·m ( $\Omega\cdot m$ ) for electrode

585 separation  $a = 2$  m.

586 Figure 8. Low-pass filtered electrical apparent resistivity ( $\rho_a$ ) map, expressed in Ohm·m  
587 ( $\Omega\cdot\text{m}$ ) for electrode separation  $\mathbf{a} = 2$  m, showing additionally the boundary separating  
588 the 2 types of soil to the NE (continuous line) and the limit of the colluvial deposits to  
589 the SW (dashed line).



Figure 1a



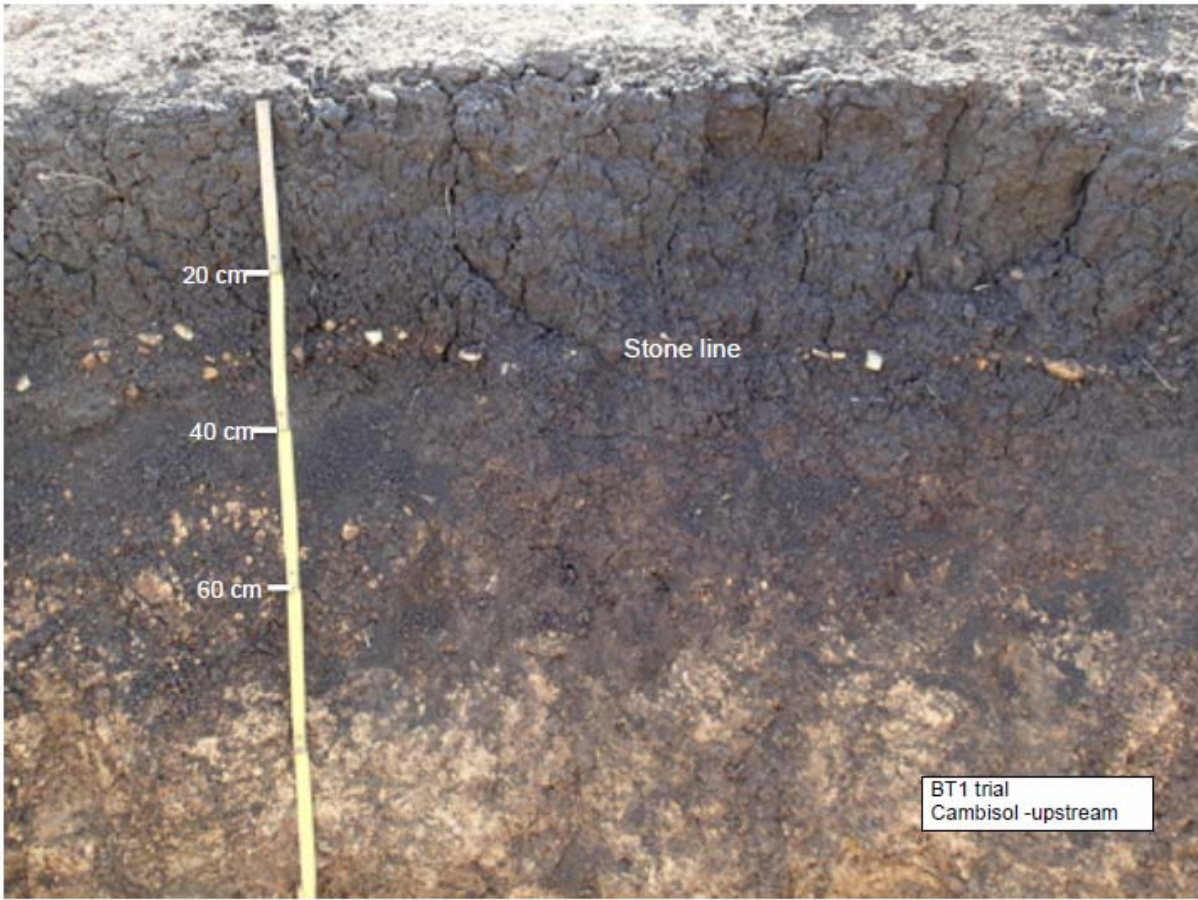


Figure 2

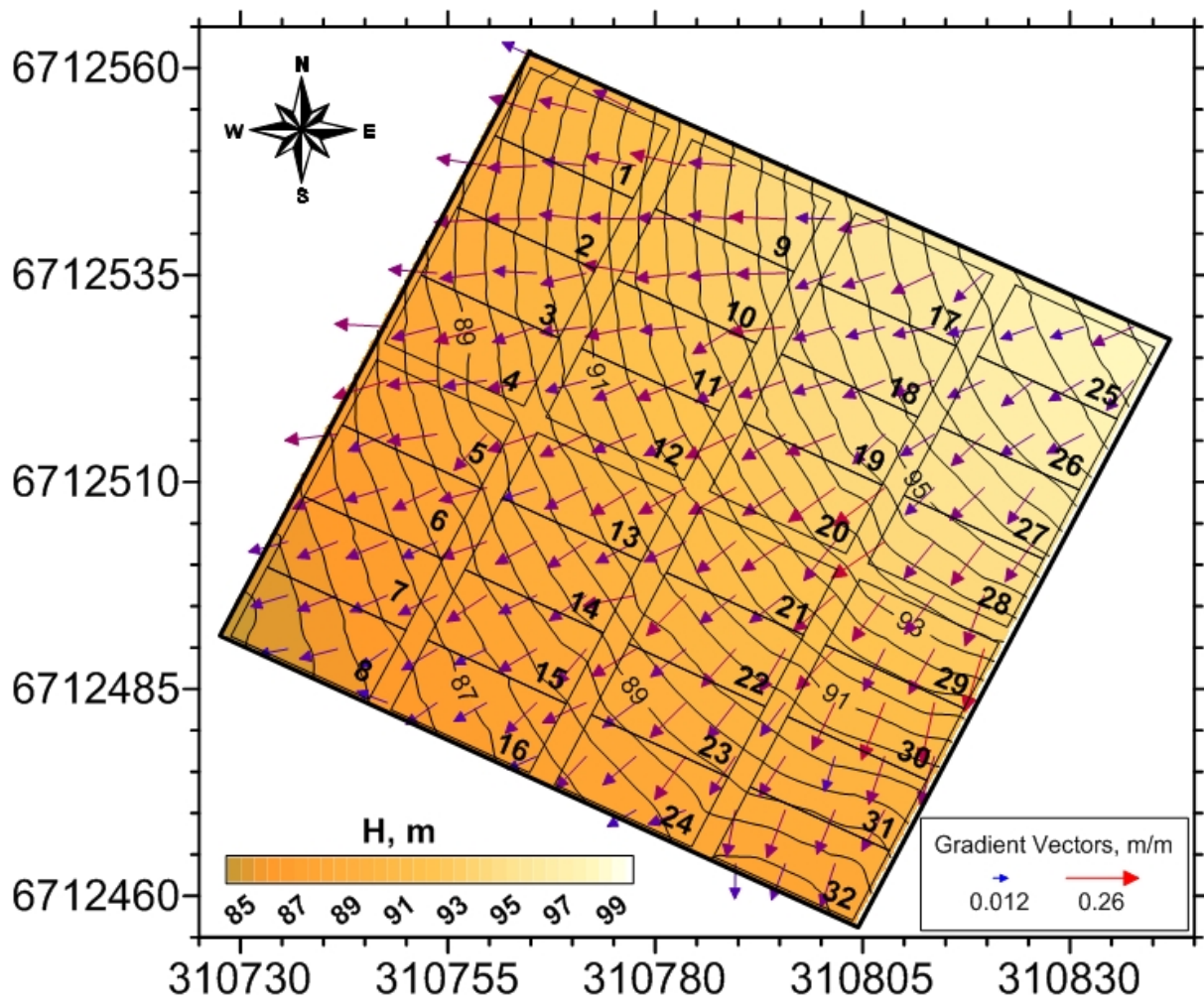


Figure 3

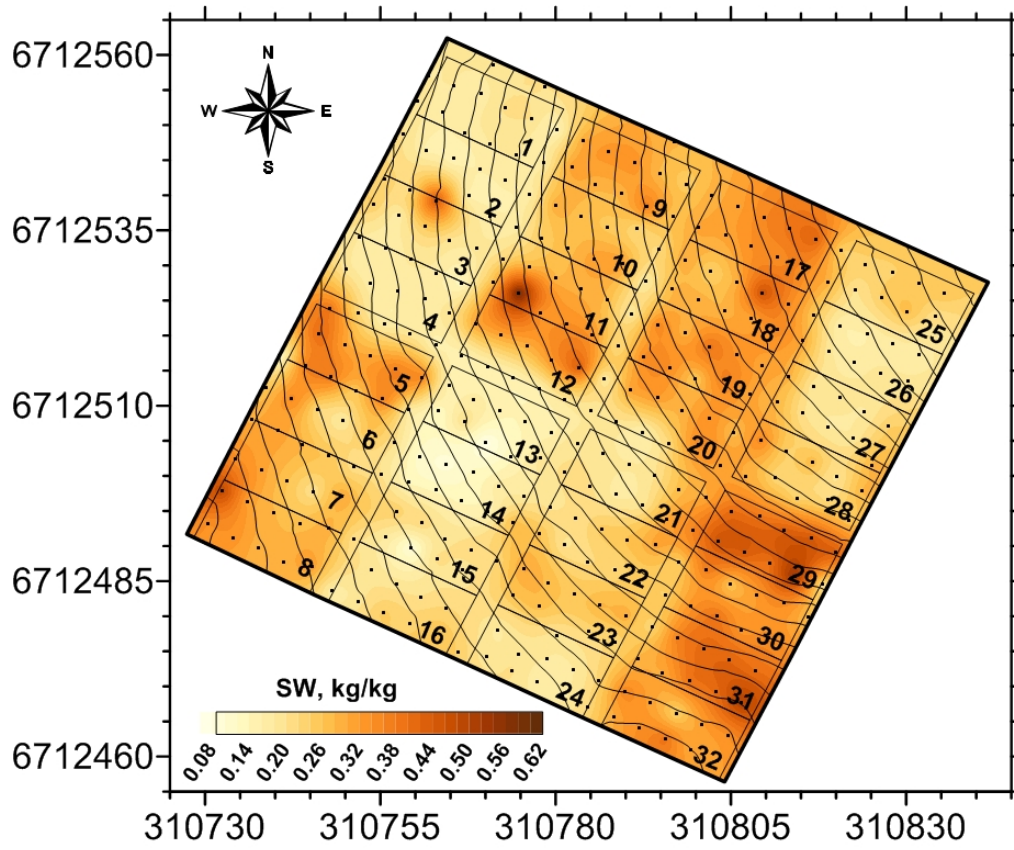


Figure 4a

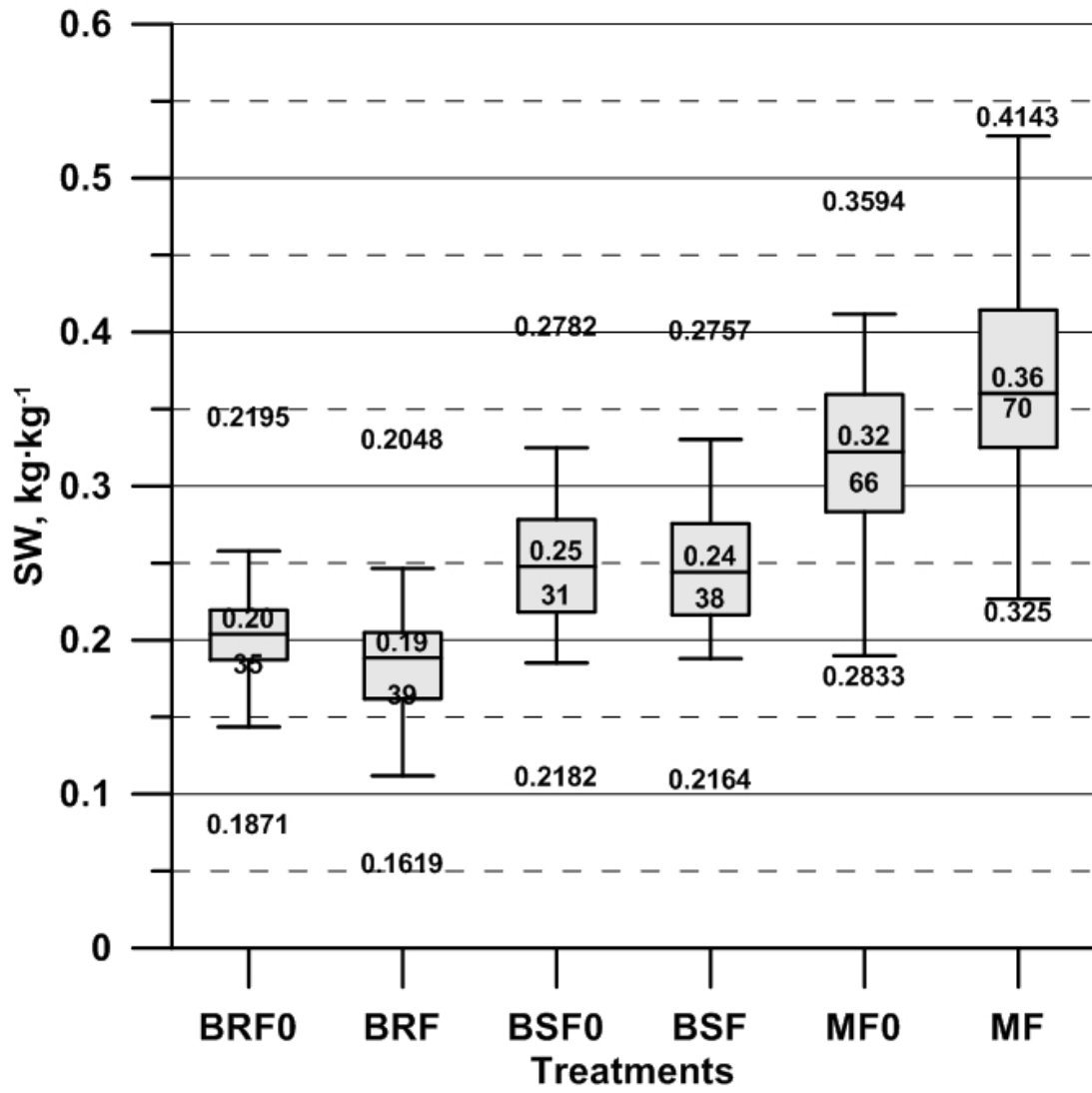


Figure 4b



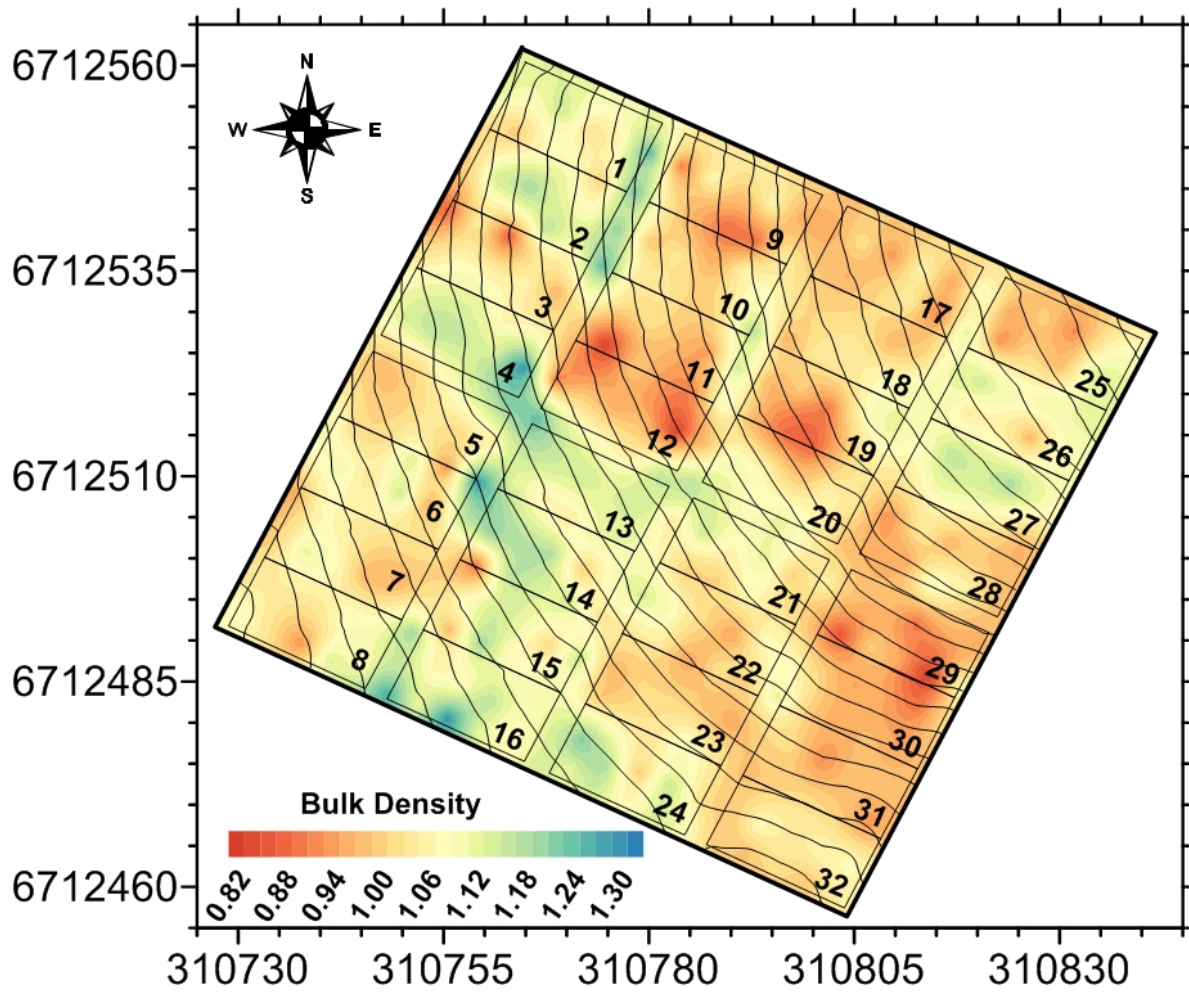


Figure 5a

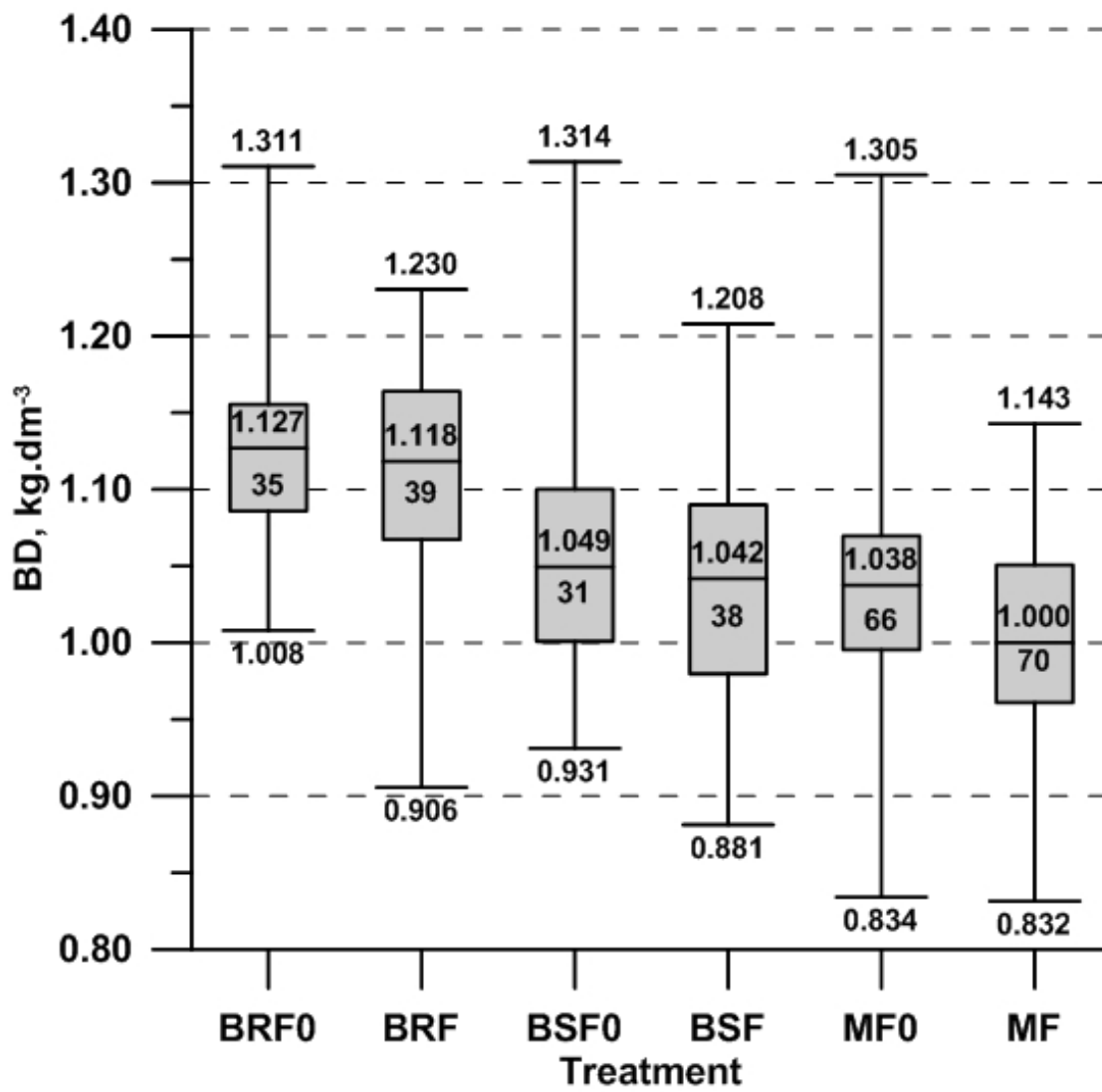


Figure 5b

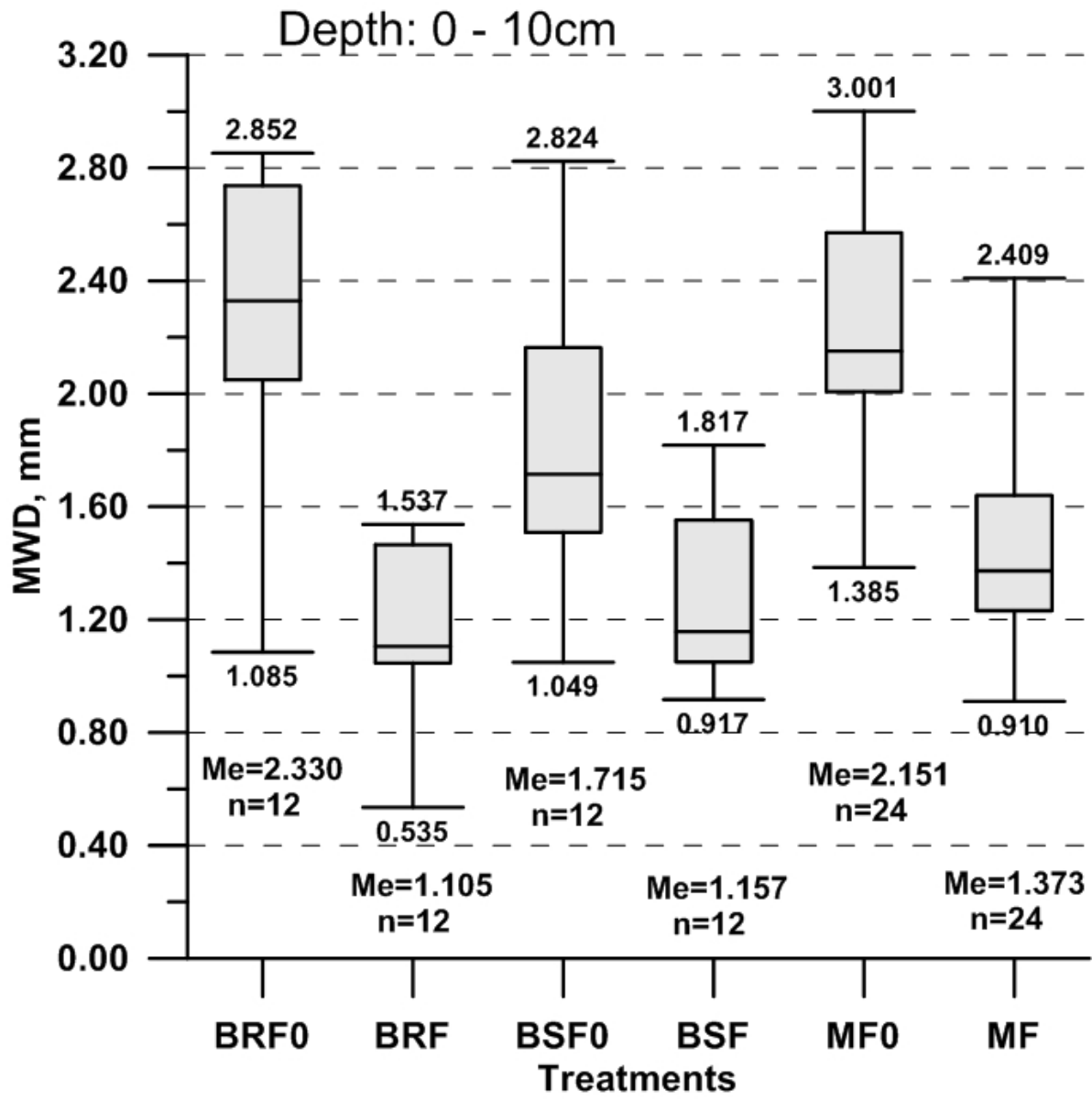


Figure 6a

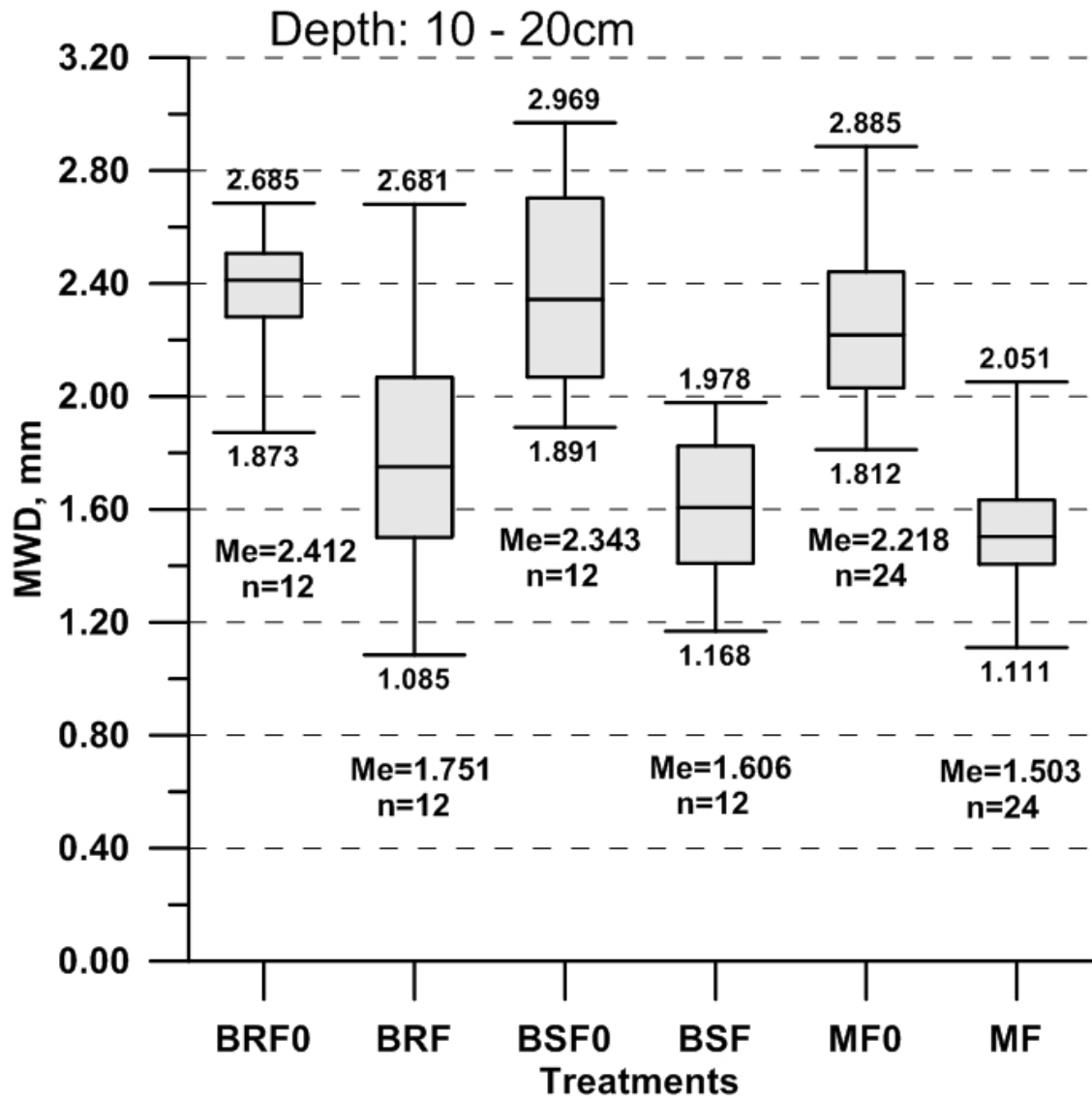


Figure 6b MWD 10 - 20cm

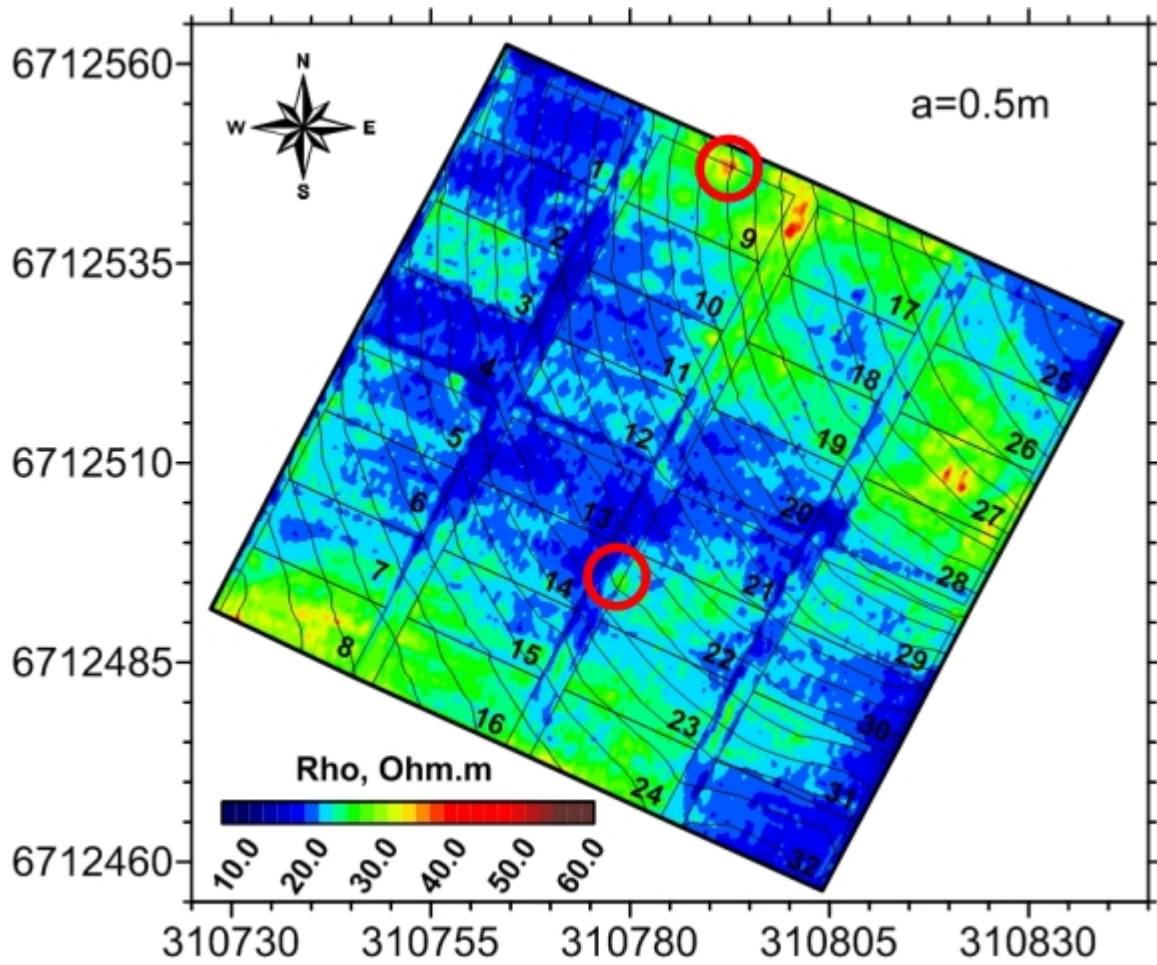


Figure 7a

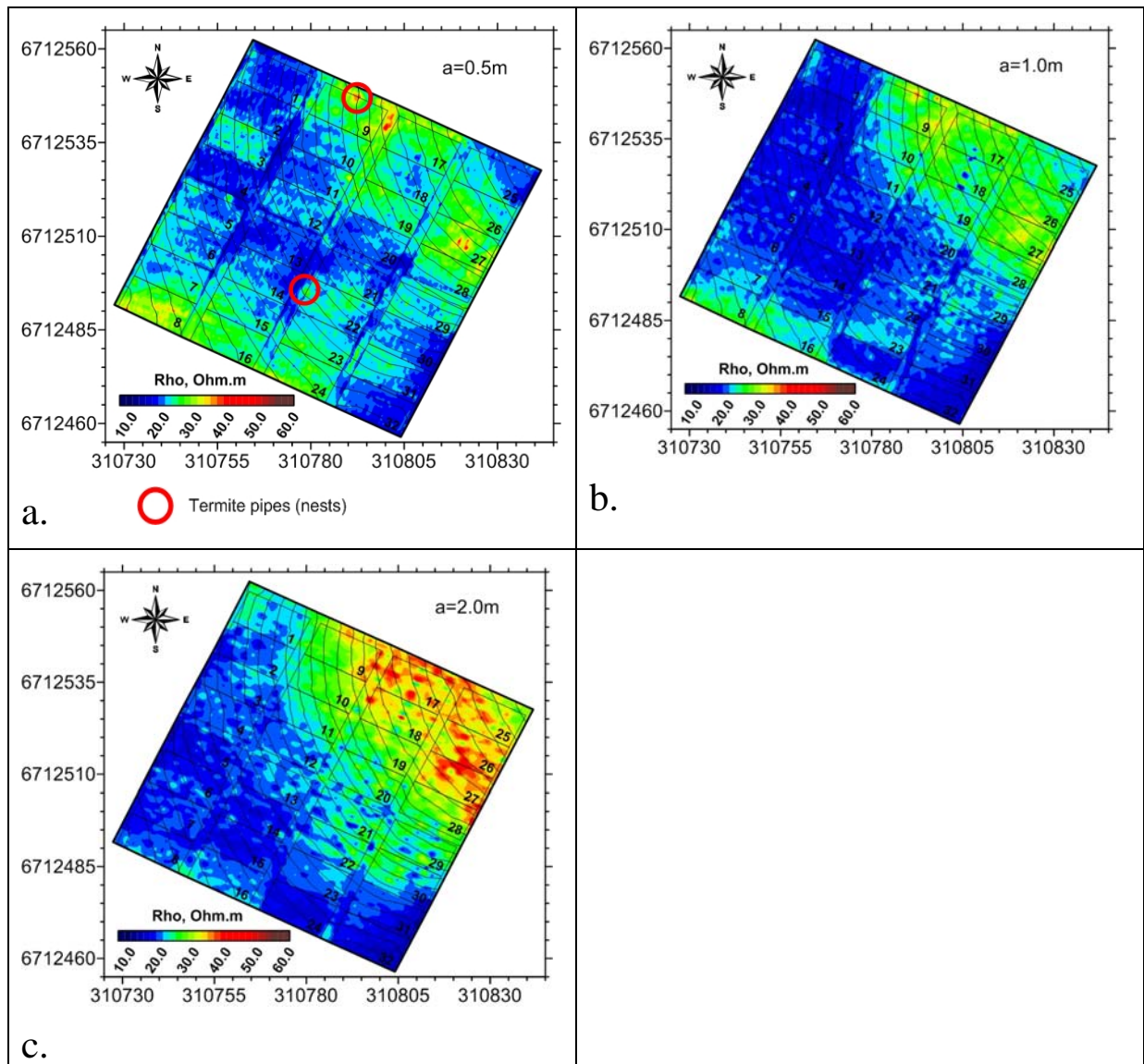


Figure 7a, b and c

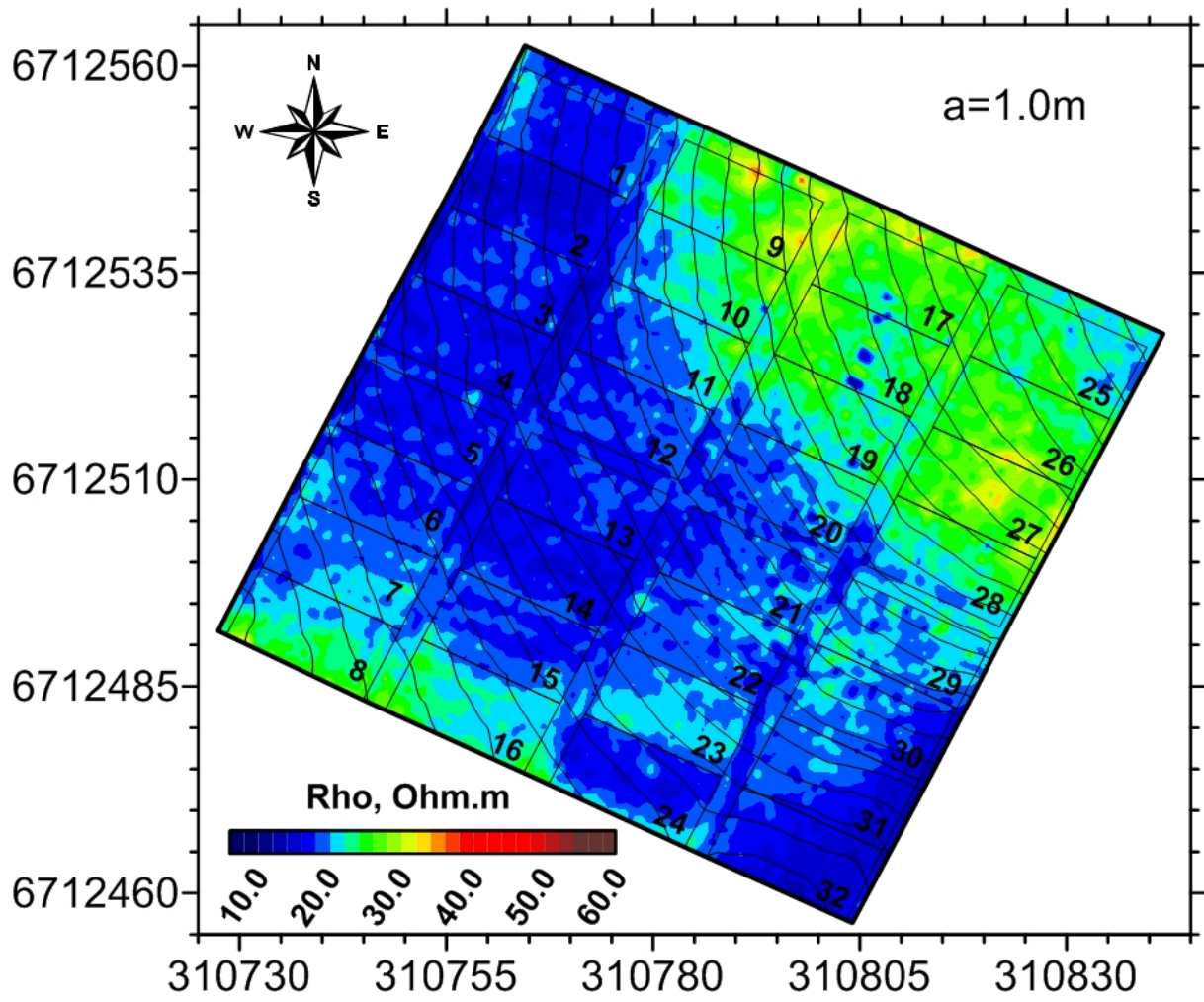


Figure 7b,

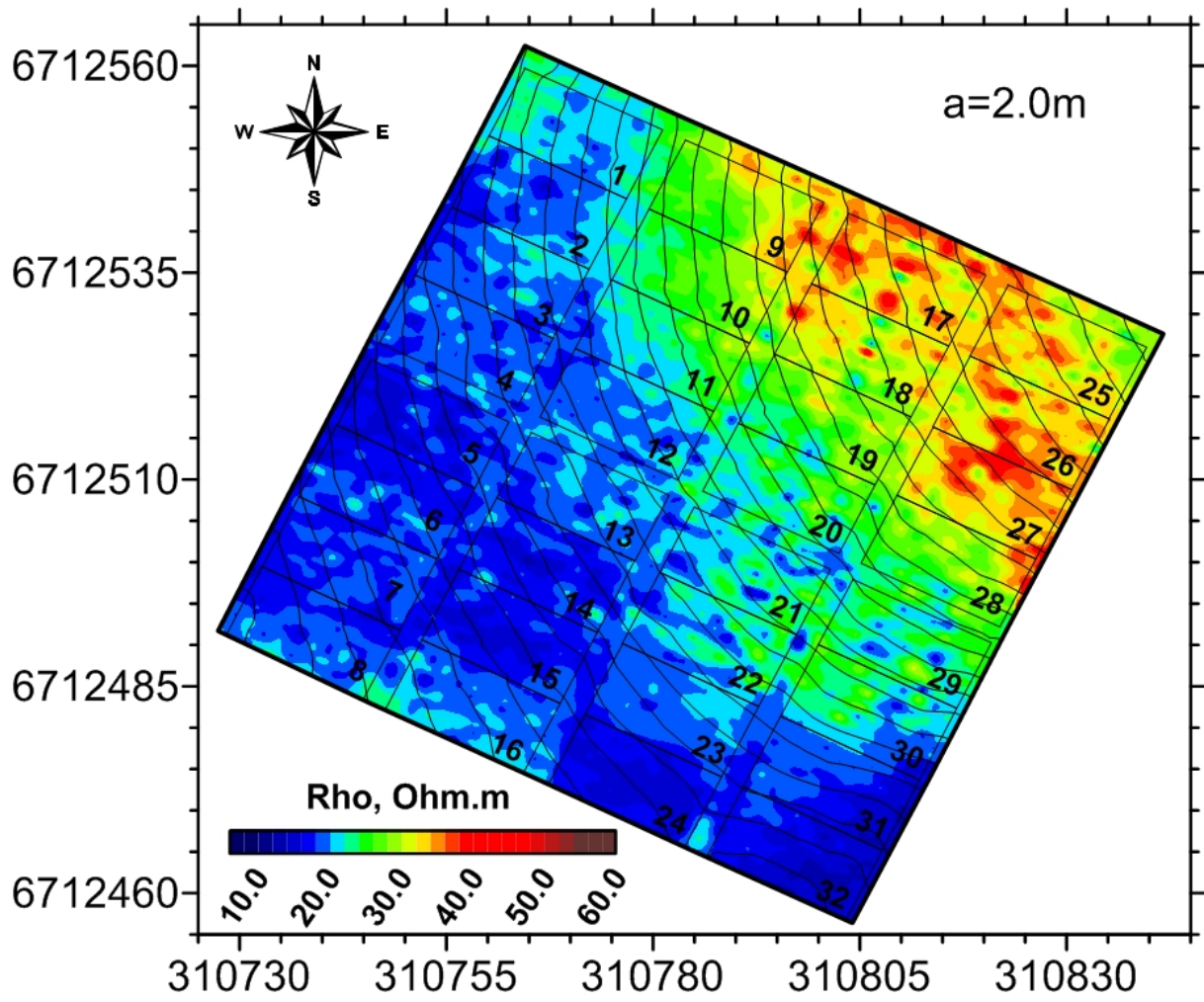


Figure 7c



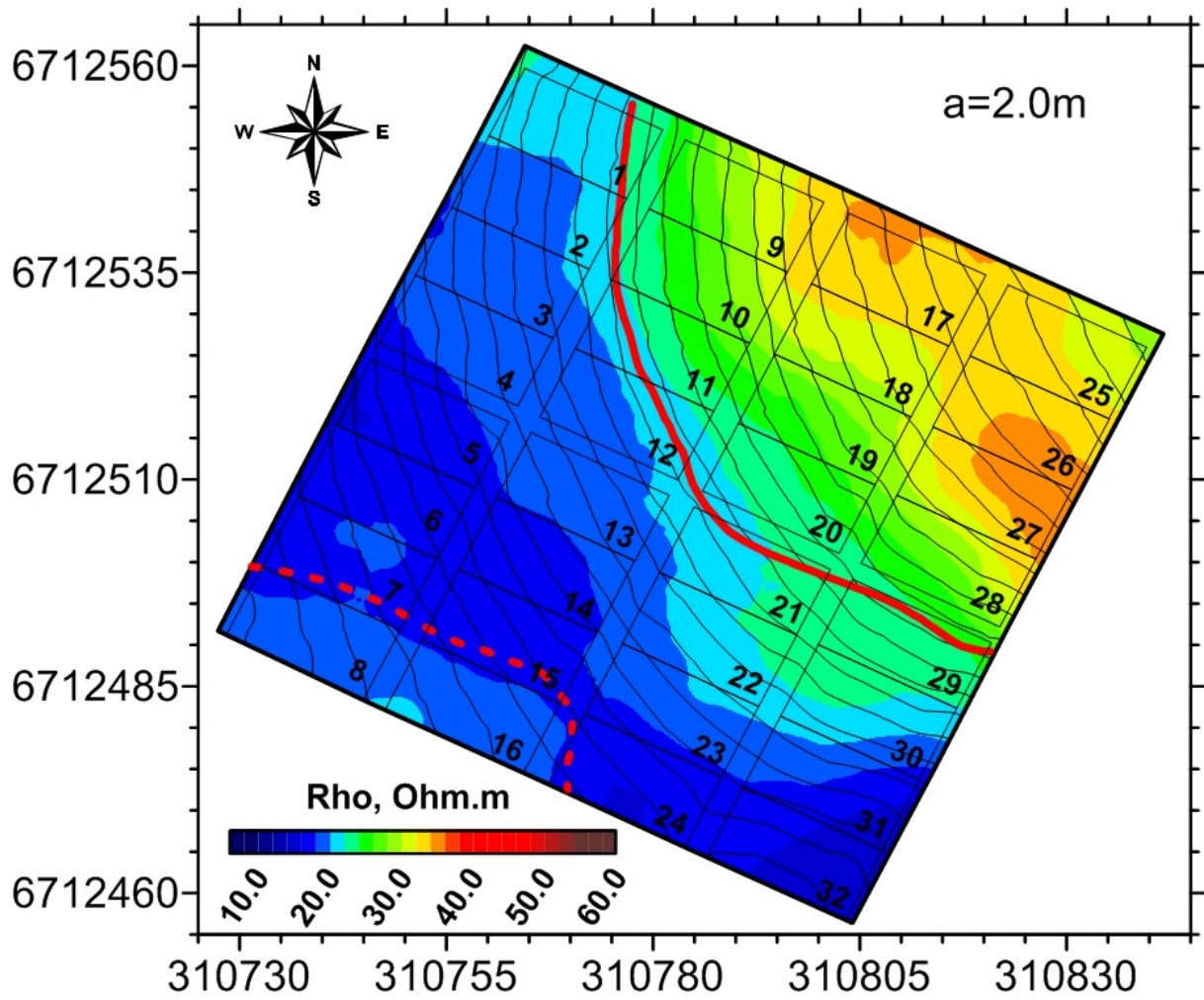


Figure 8

- Soil classification limit
- - - Limit of colluvium