



Forecasting Oligochaeta Abundance using the Apparent Electrical Conductivity of Irrigated Soils with Reclaimed Wastewater: Evidence from Corso, Algeria

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ABSTRACT

Background: The main objective of this paper is to study the possibility of using the measurement of apparent electrical conductivity (ECa) to estimate Oligochaeta (earthworm) density in irrigated soils treated with reclaimed wastewater. Additionally, the study sought to analyze the impact of using reclaimed wastewater for irrigation on earthworm density in the study area.

Methods: Earthworm sampling was carried out at thirty emplacements within the study area during two measurement campaigns. Soil ECa was measured by (EM38).

Result: The results showed that irrigation with reclaimed wastewater promotes the abundance of earthworms (earthworm density). Indeed, sites irrigated with reclaimed wastewater have higher earthworm densities compared to sites irrigated with conventional water. The results also show a strong correlation between ECa and earthworm density ($R^2 > 0.7$). The Wilcoxon test indicates a non-significant difference between measured earthworm densities and those predicted by ECa ($p > 0.5$). This result confirms the effectiveness of the EMI technique as a tool to evaluate the spatial variability of soil biological parameters. These results collectively suggest that ECa represents a real possibility of reducing the number of earthworm samplings, while ensuring the reliability of the estimates of real values of earthworm density and their surface spatial distribution. ECa could therefore be a useful tool to spatialize and predict the presence of earthworms in soil irrigated by reclaimed wastewater.

Key words: Apparent electrical conductivity, Earthworm, Wastewater.

INTRODUCTION

Earthworms play a major role in promoting soil functioning and in ecosystems services (Brown *et al.*, 1999; Cenci and Jones, 2009; Kapila *et al.*, 2021; Yadav *et al.*, 2022). They have a positive influence on organic matter dynamics and soil structure (Brown *et al.*, 1999; Çerçi *et al.*, 2020; Ramesh *et al.*, 2020). The spatial variability of earthworms will likewise influence ecosystem functions such as litter decomposition and nutrient cycling (Ettema and Wardle, 2002; Valckx *et al.*, 2009).

In fact, since the soil is their natural environment, earthworm abundance is strongly affected by agricultural practices, such as the use of fertilizers, organic and mineral the type of irrigation practiced and the quality of irrigation water (Chan and Munro, 2001; Eijsackers *et al.*, 2005; Akilan and Nanthakumar, 2017).

This variability of earthworms has been previously studied and many methods have been derived. However, to date, no specific method has been defined as a standard (Pumpanen *et al.*, 2004; Valckx *et al.*, 2009). The uneven spatial distribution of earthworms at the field scale in a variety of ecosystems is now well accepted (Rossi *et al.*, 1997; Hernández *et al.*, 2007; Valckx *et al.*, 2009). Characterizing the within-field spatial distribution of earthworms is time, labor and cost intensive, since it relies on extensive soil sampling and subsequent soil analyses. Recently, the use of mobile, sensor-based measurements of soil apparent electrical conductivity (ECa) has proven to be a quick, easy

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and reliable method for establishing within-field spatial variability (Valckx *et al.*, 2009; Joschko *et al.*, 2010; Lardo *et al.*, 2012; Lardo *et al.*, 2015). Only a few information is available about the linkages between geophysical soil measurements and soil fauna, such as earthworms, a functionally important organism group in soils (Edwards and Bohlen, 1996). Values of ECa were found to be positively related to earthworm abundances in different soils (Deibert and Utter, 2003; Nair *et al.*, 2005). Other researchers have shown that ECa mapping can be a useful tool to represent earthworm distribution and activity (Valckx *et al.*, 2009;

Joschko *et al.*, 2010; Lardo *et al.*, 2012; Lardo *et al.*, 2015). They demonstrated that the spatial distribution of earthworm species is correctly estimated by ECa measurements. Therefore, the abundance of earthworms in soil may be identified and characterized through rapid and time-saving geophysical methods, which could reduce the number of soil samples. Thus, indeed, ECa could be a good estimator of earthworm abundance and biomass, capable of helping in the monitoring of soil quality affected by agricultural practices such as irrigation by treated wastewater. In this research, we carried out a field study on loamy clay soils irrigated by treated wastewater, where we analyzed the quantitative relationship between earthworm abundances

and ECa measured in the field. The apparent electrical conductivity was obtained by means of a portable electromagnetic instrument. The ECa data enabling to predict earthworm occurrence is tested through the comparison between estimated ECa and measured earthworm abundance. We assume that the relationship between ECa measurements and earthworm density is significant. Furthermore, we expect that ECa measurements will enable us to estimate earthworm abundance in unsampled locations.

The aims of this paper are to (i) investigate the possibility of predicting earthworm density through apparent electrical conductivity in soils irrigated by treated wastewater and (ii)

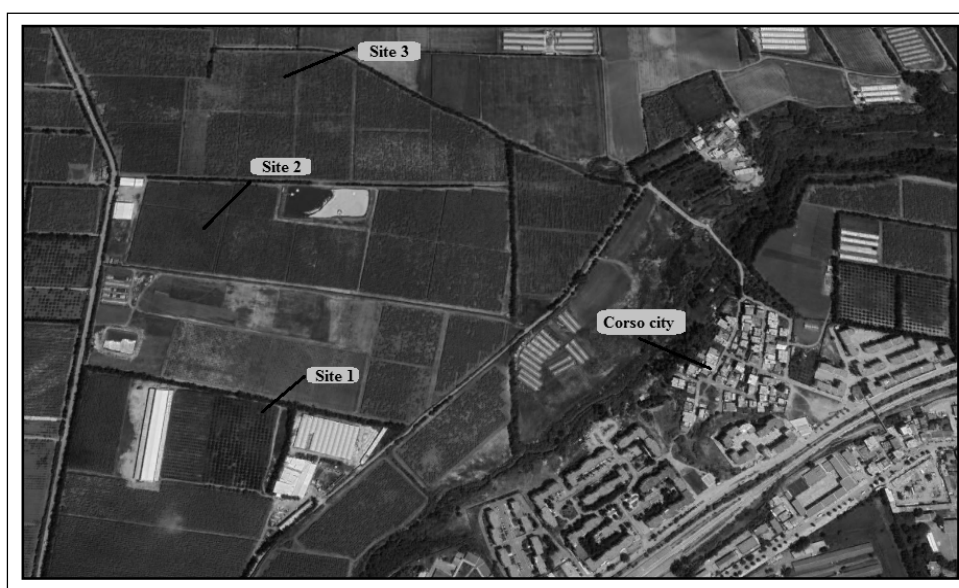


Fig 1: Location of the studied sites.

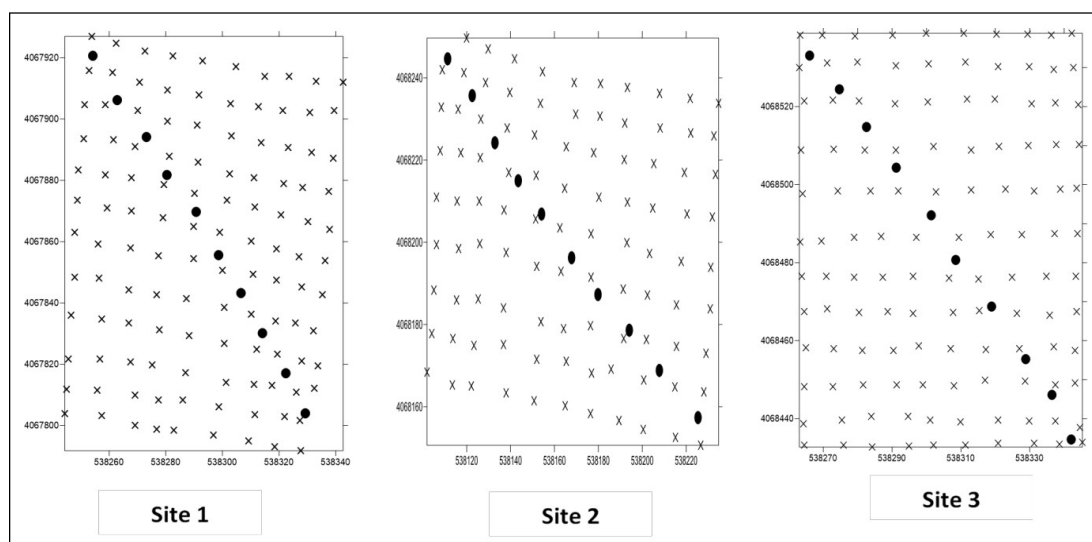


Fig 2: Locations of earthworm sample (●); soil samples (•) and ECa (•, x).

study the effect of reclaimed wastewater on earthworm density.

MATERIALS AND METHODS

Study site

This study was conducted in the Corso district, which is located in the north of Algeria, bounded by longitudes 3°25' to 3°29' East and latitudes 36°46' to 36°42' North (Fig 1). The climate is subhumid (670 mm of rain per year), temperate in winter with strong potential evapotranspiration (1073 mm). The soil classified as Calcic Luvisol (IUSS, 2014), with sandy clay loam to loam texture. Three sites of land belonging to the same soil type were chosen as the sampling grounds. The first one is a citrus irrigated by treated wastewater, the second is vineyard also irrigated by treated wastewater. The third site is vineyard irrigated by conventional water, which we consider as a control. Irrigation of the three study sites is carried out using a drip system.

Earthworm sampling

Earthworms were sampled at 30 locations within the study area during two measurement campaign in November 2021 (Campaign 1) and May 2022 (Campaign 2). Temperature and moisture conditions were favorable for earthworm sampling throughout the period (RMI, 2004; Valckx *et al.*, 2009). At each site, 10 samples were taken, with the average distance between them was 10 m (Fig 2). The size of each sample was 25×25×25 cm. Earthworm extraction from the soil samples was performed by hand sorting under good light conditions. Earthworms were rinsed in tap water, counted, blotted dry on tissue paper, weighed (0.01 g precision). All individuals were identified to species level following the nomenclature of (Boucher, 1972). Individuals were weighed with gut contents and their biomass was expressed as g.m⁻² formalin-preserved weight. Earthworm abundance for each plot was calculated by relating earthworm number and biomass to 1 m². This step of work was carried out at the Eco-biology Animals laboratory located at Higher Normal School of Kouba.

Soil sampling

In parallel, at each point of Earthworm sampling, soil samples were collected by auger in increments of 30 cm to

a depth of 90 cm for laboratory analysis. The particle size fractions, total CaCO₃ and, the pH_{water} (2/5), the water content (H%) and electrical conductivity (EC_{1:5}), organic matter (OM%) were determined for each soil layer and weighted for the 90 cm depth (Fig 2). The soil analyzes were carried out at the laboratory of the soil sciences department located at the National Higher School of Agronomy, ENSA, Algiers.

ECa measurement

The soil's ECa was measured by an electromagnetic induction sensor, an EM38 model (Geonics Ltd Canada) in the horizontal position (the coils were aligned horizontally). This instrument measures apparent soil electrical conductivity (EC) in units of millisiemens per meter (mS/m). When the EM38 is used in the horizontal mode (EM38H) on a uniform soil, 75% of the signal response is estimated to come from the top 1.8 m of soil. In the vertical mode (EM38V), 75% of the signal is estimated to come from the top 1.8 m. However, for heterogeneous soils the proportion that comes from different soil layers depends on the conductivity of those layers (Corwin and Rhoades, 1982). The principles of electromagnetic induction and soil conductivity measurements are described in detail in McNeill (1980a, b).

The ECa measurements were performed at the same locations as the soil and earthworm samples (Fig 2). This allows for the establishment of the relationship between ECa and earthworm density, assuming an equation $ECa = f(\text{earthworm density})$ for each studied site. These equations are denoted as equations 1, 2, 3, corresponding to the measurements in the sites 1, 2 and 3, respectively. simultaneously, ECa measurements were carried out to produce maps of earthworm density distribution (Fig 2). All sampling locations were georeferenced using a global positioning system (GPS) receiver with a positional accuracy of 3 to 5 m and converted into the Universal Transverse Mercator (UTM zone 31N EPSG:32631).

Statistical and geostatistical analysis

Classical descriptors such as mean, maximum, minimum and standard deviation were determined. Univariate relationships between ECa and earthworm density were studied by simple linear regression (SLR). Validation of

Table 1: Soil Characteristics of the three sites used to compare earthworm distribution.

	Site 1		Site 2		Site 3	
	Campaign 1	Campaign 2	Campaign 1	Campaign 2	Campaign 1	Campaign 2
Clay%	29.97±1.59	31.22±1.62	28.88±0.86	30.25±0.79	29.79±1.5	29.33±1.63
Silt%	27.73±1.98	29.33±1.94	29.13±2.54	29.66±2.71	28.53±1.11	30.32±1.25
Sand%	42.3±2.87	39.45±2.75	41.99±2.01	40.09±2.21	41.68±1.75	40.35±2.01
pH	7.2±0.08	7.1±0.1	7.32±0.13	7.29±0.15	7.02±0.19	6.98±0.22
EC mS/cm	0.61±0.16	0.51±0.22	0.31±0.15	0.12±0.03	0.68±0.05	0.55±0.08
CaCO ₃ %	3.53±0.47	3.88±0.53	3.52±0.64	3.82±0.71	3.21±0.62	3.11±0.54
H%	13.67±0.85	15.32±0.89	13.8±1.34	14.8±1.42	13.76±1.69	12.76±1.54
OM%	2.22±0.32	2.15±0.29	1.12±0.23	1.52±0.27	3.11±0.34	2.75±0.38

calibration equations was carried out by the Wilcoxon test. The spatial variability dependence was analyzed by applying ordinary kriging. The analysis was performed based on earthworm densities assuming that the occurrence of individuals is more important in understanding the factors controlling spatial patterns of populations than their biomass (Valckx *et al.*, 2009).

RESULTS AND DISCUSSION

Soil characteristic

The main soil characteristics of the three studied sites are summarized in Table 1.

The calculated averages of all samples indicate that the studied soil is clay loam, with a small amount of CaCO_3 (approximately 4%) and organic matter (OM) (less than 3%) and is neutral (pH approximately 7), with low water content (less than 15%) and low salinity (CE1:5 less than 1 dS/m). However, the results also show that these characteristics vary differently in space, as indicated by the standard deviations for each of parameter. Indeed, the calculations reveal that the EC, OM and CaCO_3 are the most variable

parameters with coefficient of variation (% SD/mean) ranging between 13 and 48%. On the other hand, the texture and pH present a homogeneous appearance, with variation coefficients of less than 7%. These results indicate slight differences in soil characteristics of all studied sites.

Earthworm variability

Density and biomass of the species found in the three sampling plots are presented in Table 2. In total, seven earthworm species were observed among which the *Octodrilus coplanatus* was the most abundant species in terms of biomass and density, followed by the *Alolobophora rosea* and the *Nicodrilus caliginosus*. The other species *Microscolex dubius*, *Microscolex phosphoreus*, *Alolobophora chlorotica* were less frequently encountered. *Alolobophora moebii* is the least represented species, with a density of less than 3, regardless the site location and the study campaign considered. In general, the plots did not show significant differences in terms of the abundance and biomass of earthworms. Regarding site 1, earthworm abundance ranged between 88 (campaign 2) and 138 (campaign 1) individuals m^{-2} , while earthworm biomass

Table 2: Earthworm biomass and densities as collected at each studied site. Data are given for each measurement campaign per earthworm species.

Earthworm species/ Ecological category	Abundance (ind m^{-2})	Biomass (g m^{-2})	Abundance (ind m^{-2})	Biomass (g m^{-2})	Abundance (ind m^{-2})	Biomass (g m^{-2})
Campaign 1	Site 1		Site 2		Site 3	
<i>Octodrilus coplanatus</i>	66	36,92	21	14,5	6	4,62
<i>Nicodrilus caliginosus</i>	14	8,62	5	3,3	7	5,39
<i>Alolobophora rosea</i>	36	22,15	5	3,3	2	1,93
<i>Alolobophora chlorotica</i>	4	2,46	8	5,28	/	/
<i>Alolobophora moebii</i>	2	1,23	1	0,66	2	0,39
<i>Microscolex dubius</i>	10	6,15	3	1,98	3	2,31
<i>Microscolex phosphoreus</i>	6	3,69	3	1,32	2	1,54
Total	138	81.22	46	30.34	22	16.18
Campaign 2	Site 1		Site 2		Site 3	
<i>Octodrilus coplanatus</i>	39	24,48	29	18,1	8	6,18
<i>Nicodrilus caliginosus</i>	12	7,35	8	5,17	5	4,25
<i>Alolobophora rosea</i>	21	13,06	10	6,03	2	1,55
<i>Alolobophora chlorotica</i>	4	2,45	7	4,31	2	1,16
<i>Alolobophora moebii</i>	3	1,63	3	1,72	1	0,39
<i>Microscolex dubius</i>	6	3,26	3	1,72	2	1,93
<i>Microscolex phosphoreus</i>	3	1,63	4	2,59	1	1,16
Total	88	53,86	64	39,64	21	16,62

Table 3: Linear regressions parameter between ECa and earthworm abundance for the three study sites.

Campaign 1				Campaign 2		
	Slope	intercept	R2		intercept	R2
Site 1	2.09	57.50	0.819***	4.825	-43.72	0.793***
Site 2	1.92	-38.74	0.741**	0.387	24.71	0.761***
Site 3	-0.88	48.44	0.796***	-0.674	54.57	0.772***

, * Significant at $P < 0.01$, $P < 0.001$, respectively.

varied from 54 (campaign 2) to 81 g m⁻² (campaign 1). For site 2, the abundance and biomass of earthworms were slightly lower, with values ranging between 46 (campaign 1) and 64 (campaign 2) individuals m⁻² for abundance and between 30 (campaign 1) and 40 g m⁻² (campaign 2) for biomass. On the other hand, the site 3, which does not receive reclaimed wastewater, shows significantly lower values compared to the other sites, with abundances lower than 21 individuals m⁻² and biomass lower than 16 g m⁻².

Estimation of earthworm abundance by ECa

The parameters of calibration equations that relate earthworm abundance to ECa by SLR model are presented in Table 3. The determination coefficients R² for the six equations are statistically highly significant (p<0.01) with R² ranging between 0.74 and 0.81. This result reflects strong relationships between ECa values and earthworm abundance, as it also observed by Valckx *et al.* (2009), Joschko *et al.* (2010) and Lardo *et al.* (2012) for arable fields. However, these relationships vary depending on the soil management system. The linear relationship between ECa and earthworm abundances was higher in citrus soil (site 1) than in vineyard soils (site 2 and 3). This result means that within the three sites, earthworm abundance can be properly predicted by the ECa. Moreover, the results show that the

arithmetic means of estimated earthworm abundance are similar to those of measured earthworm abundance (Table 4). This suggests that the ECa estimate correctly the earthworm abundance. Indeed, calculations show that the correlations between the abundance of earthworms measured and that estimated by ECa are statistically very highly significant ($0.87 \leq r \leq 0.91$; $p < 0.001$) (Table 5). The comparison between the measured and predicted values of earthworm abundance for the different study sites is illustrated in Fig 3. This figure shows that the curves of measured earthworm abundance are very close to those estimated by ECa, slightly lying above or below them, except for the first two observations at site 1 and 2 (campaign 1). This result means that the earthworm abundance prediction using ECa is reliable with only a very slight over or underestimation. Non-parametric Wilcoxon tests (Table 6) confirm this result and indicate that the differences between the values of earthworm abundance measured and those predicted by ECa were not statistically significant. Similarly, this result confirms that, in the context of this study, the earthworm abundance can be properly estimated by ECa.

The spatial distribution of earthworm abundance estimated by ECa for each study site is shown in Fig 4. Observing the maps of site 1 and 2 (irrigated by treated wastewater) confirms the results obtained previously (Table

Table 4: Descriptive statistics of earthworm abundance measured and earthworm abundance estimated by ECa.

	Campaign 1				Campaign 2			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Site 1								
Earthworm abundance measured	75	170	132.1	30.75	45	120	85.1	24.11
Earthworm abundance estimated	95.1	174.5	132	27.84	47.8	115.2	84.8	21.42
Site 2								
Earthworm abundance measured	12	76	43.7	26.20	36	95	63.3	19.01
Earthworm abundance estimated	15.1	88.1	43.68	22.57	41.2	96.5	63.2	16.63
Site 3								
Earthworm abundance measured	10	32	20.4	7.86	10	32	20.7	7.66
Earthworm abundance estimated	12.3	30.8	20.3	7.01	8.9	30.48	20.6	6.73

Table 5: Correlation between measured and predicted earthworm abundance.

	Campaign 1	Campaign 2
Site 1	0.91***	0.89***
Site 2	0.86***	0.87***
Site 3	0.89***	0.88***

, * Significant at $P < 0.01$, $P < 0.001$, respectively.

Table 6: Wilcoxon test between earthworm abundance measured and earthworm abundance predicted by ECa.

	Campaign 1	Campaign 2
Site 1	0.846*	0.979*
Site 2	0.432*	0.922*
Site 3	0.981*	0.695*

*Significant at $P < 0.05$.

1 and 2) and highlights the significant variability in the abundance of earthworms for both measurement periods. Indeed, the maps reveal that site 1 (cultivated by citrus) has higher values compared to site 2 (cultivated by vine). Moreover, more than 80% of the sites are occupied by densities greater than 60 (ind.m⁻²). When compared to the other sites, the maps of site 3 present a certain spatial

homogeneity regardless of the measurement campaign and the depth levels. This homogeneity is more pronounced during the first campaign (Nov 2021). These results confirm the findings of the regression tests and the Wilcoxon tests, demonstrating that the abundance of earthworms can be accurately estimated and mapped through ECa.

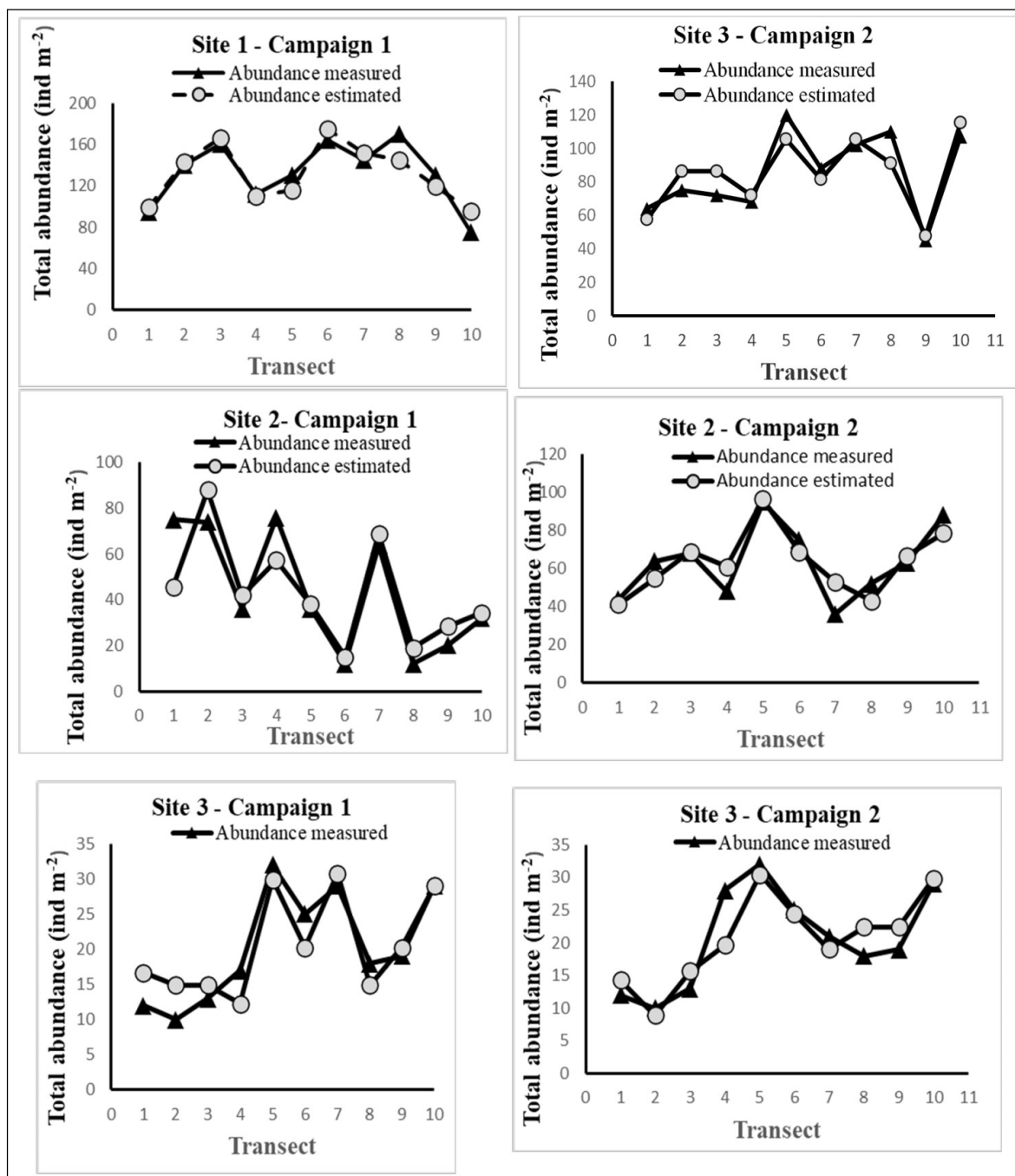


Fig 3: Comparison between measured and estimated abundance of earthworm at each site study.

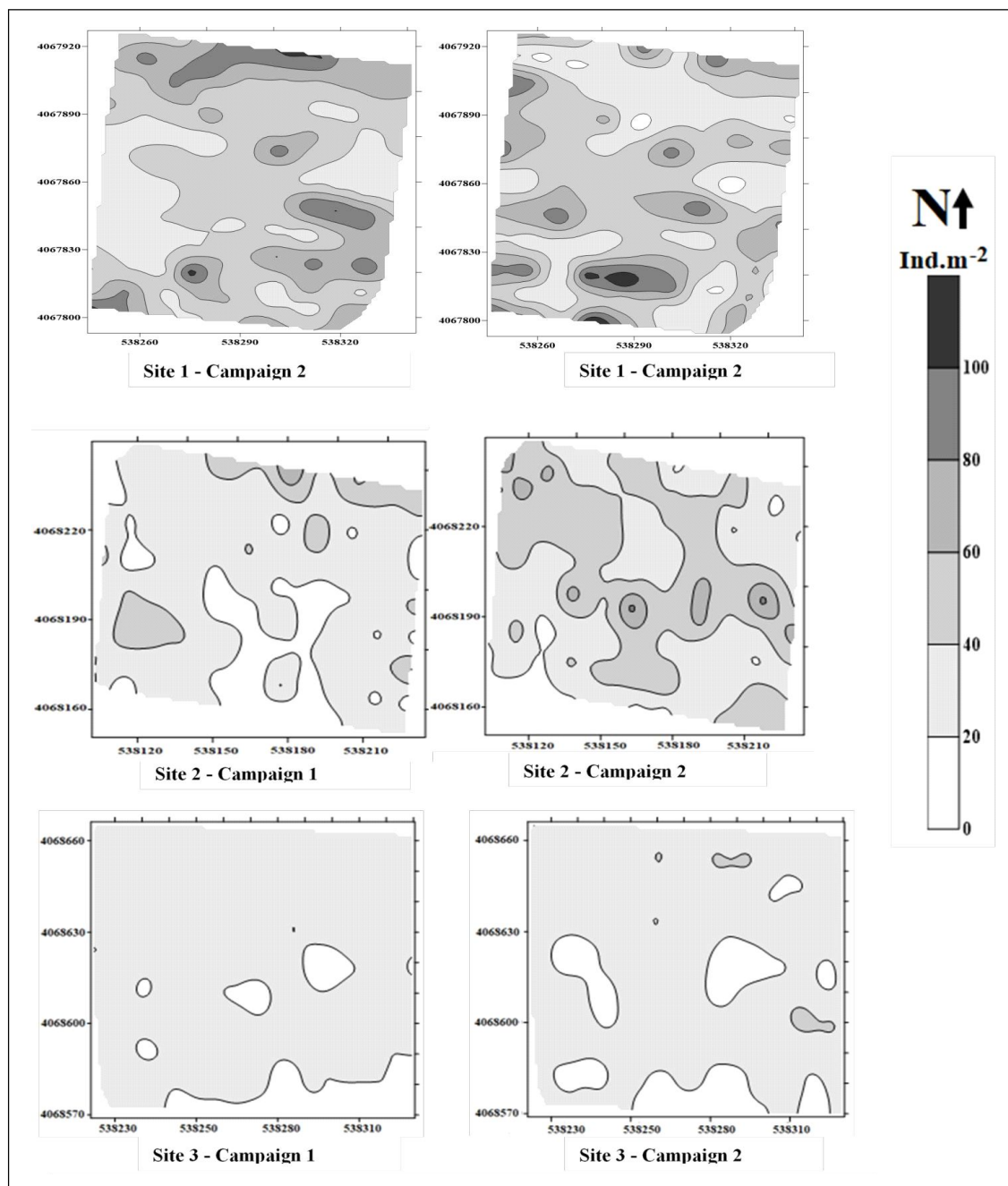


Fig 4: Kriged contour maps of the earthworm abundance (ind m^{-2}) estimated by ECa at each study site.

CONCLUSION

The aims of this paper were to investigate the possibility of predicting earthworm density through apparent electrical conductivity on irrigated soils by reclaimed wastewater and to analyze the effect of reclaimed wastewater on earthworm density. The entirety of the results shows that the density of earthworms can be well estimated and mapped through ECa. The results showed that irrigation by treated wastewater promotes the abundance of earthworms. Indeed, the sites irrigated with treated wastewater have higher

earthworm densities compared to the sites irrigated by conventional water. The results also show a strong correlation between ECa and soil earthworm abundance, confirming the EMI technique as a useful tool for evaluating the spatial variability of soil biological parameters. This study allowed us to spatialize punctual ECa data at field scale. ECa spatialization provided a more detailed distribution of earthworm density within the vineyard and citrus fields. The EMI technique could be a useful tool for accurately computing the overall earthworm density, which is a difficult

parameter to measure due to species' high mobility in the soil. The EMI technique appears to be a very efficient tool for spatializing earthworm density and biomass at the field level and for locating representative soil sampling areas. Therefore, the ECa method combined with the geostatistical technique seems to be reliable for estimating the mean value of earthworm density and they could become an effective strategy to reduce the number of soil samplings and, consequently, the cost of the evaluation procedure. This study confirms the results obtained previously and demonstrates the effectiveness of geophysical methods for predicting the biological parameters of the soil. However, more detailed studies on the evaluation of soil biological parameters through ECa are needed, especially in very different pedoclimatic scenarios.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Conflict of interest

All author declare they have no conflict of interest.

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