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The apparent electrical conductivity as a surrogate variable for predicting earthworm abundances in tilled soils

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Abstract

Noninvasive geophysical methods have a great potential for improving soil-biological studies at field or regional scales: they enable the rapid acquisition of soil information which may help to identify potential habitats for soil biota. A precondition for this application is the existence of close relationships between geophysical measurements and the soil organism of interest. This study was conducted to determine whether field measurements of apparent electrical conductivity (ECa) are related to abundances of earthworms in tilled soils. Relationships between ECa and earthworm populations were investigated along transects at 42 plots under reduced and conventional tillage at a 74 ha field on sandy-loam soil in NE Germany. Relations were analyzed with linear-regression and spatial analysis.

The apparent electrical conductivity (ECa) was quantitatively related to earthworm abundances sampled 5 months after the geophysical measurements. No relationship was found, however, in plots under conventional tillage when analyzed separately. If earthworm abundances were known at every other location along the transects and if the state-space approach was used for analysis, the analysis of ECa measurements and earthworm abundances indicated that 50% of the earthworm samples could have been substituted by ECa measurements. Further research is needed to fully evaluate the potential of ECa measurements for predicting earthworm habitats in tilled soil.

Key words: apparent electrical conductivity / state-space analysis / earthworm abundance / conventional tillage / reduced tillage / sandy soil

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1 Introduction

Noninvasive geoelectrical methods are increasingly used in soil science and related disciplines (*Corwin* and *Lesch,* 2003). With these approaches, easily observable variables may be obtained which are related to functionally important soil properties (*Sudduth* et al., 2005; *Wendroth* et al., 2006; *Weller* et al., 2007; *Lück* et al., 2009). The apparent electrical conductivity (ECa), for instance, is related to soil water content, soil texture, organic-matter content, and salinity (*Bronson* et al., 2005; *Chen* et al., 2004; *Corwin* and *Lesch*, 2003; *Domsch* and *Giebel,* 2004). Soil texture is usually the main factor determining ECa on mineral soils because other properties contributing to soil ECa such as soil water content are affected by soil texture as well (*Domsch* and *Giebel,* 2004; *Lück* et al., 2009).

Many soil properties coded by ECa, such as texture, are important for soil biota and often determine their distribution or activity. Thus, the geoelectrical analysis of soils has a great potential for facilitating and improving soil-biological studies at field or regional scales (*Johnson* et al., 2004; *Joschko* et al., 2006). With geoelectrical methods, potential habitats for biota in soils may be characterized. Recently, ECa mapping has successfully been applied in soil-microbiological studies in agricultural soils (*Johnson* et al., 2004). However, the potential of the ECa approach has yet to be fully exploited with reference to soil-biota distribution and activity.

Only little 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), however, often only general relationships between certain soils characterized by apparent potential electrical conductivity measured in the laboratory and average earthworm populations were described (*Deibert* and *Utter*, 2003; *Nair* et al., 2005). Information about field-scale variability of ECa and its relation to earthworm abundances is scarce; so far only one study has addressed this problem (*Valckx* et al., 2006). It is therefore still relatively unknown how ECa information is quantitatively related to earthworm distributions in tilled soils. It is moreover

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not clear, whether field-scale ECa measurements are suited for predicting earthworm abundances in unsampled locations.

To bridge this gap in our knowledge, we carried out a field study on sandy tilled soil, 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 geoelectrical instrument. The power of ECa data for predicting earthworm occurrence was tested by comparing estimations based on ECa data with measured earthworm abundances. At the studied site, close relations between earthworm abundances and soil properties such as soil texture have been ascertained (*Joschko* et al., 2009). We hypothesized that the relationship between measurements of ECa and earthworm populations should be close. Furthermore, we expect that measurements of ECa will allow predictions of earthworm abundances in unsampled locations.

2 Material and methods

2.1 Study site and experimental design

The study was carried out in a 74 ha field belonging to the Komturei Lietzen (Märkisch-Oderland, Brandenburg, NE Germany) on highly variable sandy loam. Detailed information about the site is found in *Joschko* et al. (2009). Within this field, 42 plots (2 m × 15 m) are permanently installed in four transects following the main slope (aspect) and tillage direction. Average distance between plots is 70 m (Fig. 1). One part of the field is under conventional tillage (plow 25 cm), one part is under reduced tillage since 1996 (precision cultivator, 15–18 cm tillage depth). The crop rotation is cereal-dominated, with maize planted in 2005 (see *Joschko* et al., 2009).

2.2 Geoelectrical measurements

Geoelectrical measurements were carried out on July 15, 2005 at the 42 earthworm-sampling locations with a "4-Point light" earth-resistivity meter (LGM Lippmann, Germany, Fig. 2a).The instrument is based on the so called 4-point method (Fig. 2b): Two electrodes (A, B) were injecting low-frequency alternating current into the soil while another pair of electrodes (M, N) formed the potential probes which were measuring the voltage drop. In our case, the four electrodes were arranged on a line with an equal spacing (Fig. 2b). This type of electrode configuration is known as the Wenner array (*Parasnis,* 1997). Depth of investigation is controlled by the electrode spacing. To investigate the topsoil, a spacing of 0.5 m was selected. Depth response of this electrode arrangement is shown in Fig. 2b by normalized depth of investigation characteristics (NDIC). The peak of the depth-response function was located at a depth of ≈ 0.17 m (Fig. 2b, middle). From the cumulative depth response (Fig. 2b, bottom) one can tell, for instance, that the instrument received 70% of its signal within a depth of ≈ 0.38 m (Fig. 2b). The NDIC as shown in Fig. 2b is only valid for homogeneous ground. The occurrence of soil layers with contrasting ECa can slightly modify the NDIC. However, temporal changes of ECa due to different water content will not influence the NDIC on these soils which are relatively well drained. Thus, we can assume temporal stability of ECa patterns (but not the absolute values) over time, and additional analysis of water content is unnecessary to study ECa–earthworm relationships. Further discussion and case studies of stability of ECa patterns can be found in *Sudduth* et al. (2003), *Schmidthalter* et al. (2003), *Domsch* and *Giebel* (2004), and *Lück* et al. 2009. During our measurements, the instrument and the electrodes were mounted on a handheld frame (Fig. 2a). Four measurements were made within 2 m distance to the earthworm-sampling location. Averaged ECa readings from each location were used for further analysis.

2.3 Earthworm sampling

At each of the 42 plots, earthworm abundances were determined after the maize harvest which occurred on November 2–8, 2005. Earthworms were sorted by hand immediately after sampling one 50 cm × 50 cm × 20 cm (width, length, depth) soil block, excavated in a distance of 1–2 m to the

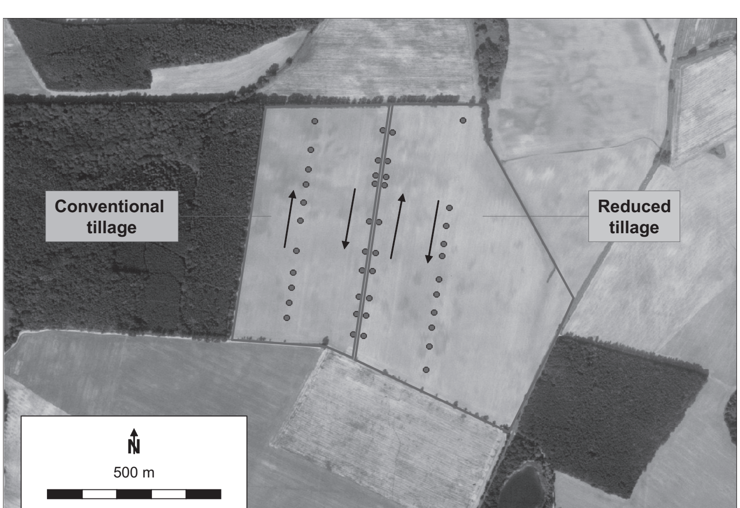
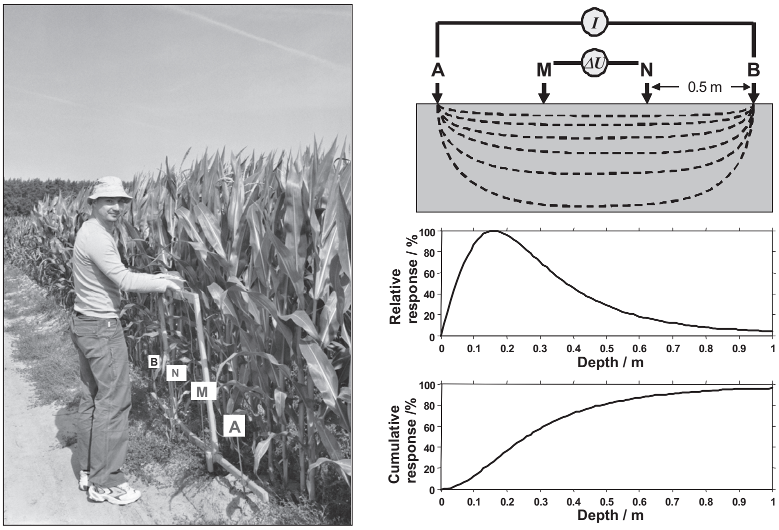


Figure 1: Lietzen site with 21 plots under conventional tillage (left) and 21 plots under reduced tillage (right). Arrows indicate direction of spatial analysis (photo: Landesvermessung and Geodatenbasisinformation Brandenburg).



a) b)

Figure 2: a) Measurement of soil electrical conductivity with the 4-Point light earth resistivity meter, b) sketch of Wenner array and depth response curves (A and B: current electrodes, M and N: potential electrodes; relative depth response at an electrode spacing of 0.5 m).

southern edge of the study plots (Fig. 1). The worms were counted and analyzed to species according to *Sims* and *Gerard* (1985).

2.4 Soil sampling and analysis

Standard analyses were carried out on composite soil samples taken in September 2004 from 0–15 cm (soil texture: 0–30 cm), at a maximal distance of 2–3 m from the earthworm-sampling locations (for details see *Joschko* et al., 2009).

Soil texture was determined by wet-sieving and sedimentation with Köhn-Pipette method after organic-C destruction with H_2O_2 and chemical dispersion using $Na_4P_2O_7$ (*Hartge* and *Horn*, 1992). The content of fine particles (FP) was calculated from total clay content plus content of fine silt (< 0.0063 mm). Total soil C was analyzed after dry combustion at 1250°C using a CNS-2000 analyzer (LECO, Ltd., Mönchengladbach, Germany) (*Deutsches Institut für Normung*, 1996). Carbonate C was determined after application of phosphoric acid by electric-conductivity measurement of CO_2 evolution (*Schlichting* et al., 1995). Organic-C content was calculated as the difference of total C and carbonate C.

2.5 Statistical analysis

Earthworm abundance for each plot was calculated by relating earthworm number and biomass to 1 m^2. For comparison of the two tillage systems, median values were calculated. To evaluate relationships between ECa, earthworm abundance, and soil properties, Spearman rank correlation coefficients were calculated.

For further statistical analyses, the following transformations were carried out: Earthworm abundances were log-normally distributed, therefore a log-transformation [ln(x+1)] was carried out. ECa data were log-transformed as well (ln x). Subsequently, linear-regression analysis was used throughout. All statistical analysis were performed with STATISTICA (version 7.0).

For state-space analysis, variables selected for the state vector have to show autocorrelations and cross correlations (*Nielsen* and *Wendroth,* 2003); this was the case with respect to ECa and earthworm abundances from November 2005.

Subsequently, state-space analysis was carried out according to *Nielsen* and *Wendroth* (2003). First, the data were normalized. For analysis, the program STATE (R. Shumway, provided by courtesy of Ole Wendroth) was used. The data were analyzed as if the plots were equally spaced. The data from four transects were plotted as a continuous sequence, beginning with the first plot of the left transect and ending with the first plot of the right transect (Fig. 1). To analyze the spatial relations between ECa and earthworm abundances and to test the prediction quality of ECa measurements for estimating earthworm activity, data values of the dependent variable (earthworm abundance, *i.e.*, individuals per m^2) were omitted according to procedures described in *Nielsen* and *Wendroth* (2003); the first value of each series was always considered in the analysis. Omitted values were then estimated from spatial dependencies of this variable on the ECa.

3 Results

Earthworm abundances in November 2005 at the Lietzen site ranged between 0 and 100 individuals per m^2; earthworm biomass varied between 0 and 31.6 g fresh weight m^{-2}. Earthworm number and biomass were closely related (r_s = 0.90); therefore only earthworm abundances were used in further analyses.

Earthworm species at the site were *Aporrectodea caliginosa* (Savigny, 1826) (52% of all individuals), *Lumbricus terrestris* Linnaeus 1758 (28%), and *A. rosea* (Savigny, 1826) (20%). Earthworms were more abundant under reduced tillage compared to conventional tillage (Tab. 1). The relationship between earthworm abundance and soil texture was slightly closer in plots under reduced tillage compared to plots under conventional tillage (Tab. 1).

Table 1: Median values of earthworm abundances and biomass and relationship between earthworm abundances and soil texture (Spearman rank correlation coefficent r_s, $p < 0.05$), Lietzen, November 2005.

	All plots ($n = 42$)	**Conventional tillage** ($n = 21$)	**Reduced tillage** ($n = 21$)
Abundance / m^{-2}	4	4	8
Biomass / g fresh weight m^{-2}	1.54	0.96	1.88
Relationship to soil texture / % fine particles	0.71	0.68	0.74

The apparent ECa, measured at discrete points site along four transects in May 2005, varied between 7.6 and 38.5 mS m^{-1} and was closely related to soil texture (fine-particles content, $r_s = 0.70$); relationships to soil organic C were less close and restricted to plots under reduced tillage (Tab. 2). The

Table 2: Relationship between apparent electrical conductivity (ECa), soil properties, and earthworm abundance; Spearman rank correlation coefficient, $p < 0.05$.; fine particles < 0.0063 mm.

	All plots ($n = 42$)	**Conventional tillage** ($n = 21$)	**Reduced tillage** ($n = 21$)
Fine particles / % (0–30 cm)	0.70	0.63	0.77
Organic C / % (0–15 cm)	0.39	n.s.	0.72
Organic C / % (15–30 cm)	n.s.	n.s.	0.76
Earthworm abundance / m^{-2}	0.54	n.s.	0.73

n.s. = not significant

Spearman rank correlation coefficient indicated a positive relationship between ECa values and earthworm abundance ($r_s = 0.54$) which upon further inspection was only found to be significant in plots under reduced tillage ($r_s = 0.73$) (Tab. 2).

Regarding the spatial patterning, ECa values showed considerable spatial variability which was, however, not random, but was characterized by increasing and decreasing trends along the sequence of measurements (Fig. 3). Earthworm abundances in November 2005 were slightly less variable (Fig. 3), but fluctuated also along the sequence. Earthworm abundances were related to ECa values in several sections of the sequence (Fig. 3). The relationship between ECa and earthworms seemed to be closer under reduced tillage in certain sections where earthworm abundance followed the ECa line in parts very closely, with pronounced coincidences at extreme points. In contrast, under conventional tillage, the distances between both lines were larger, and no clear coincidence of data progressions was present. Thus, relationships between ECa values and earthworm abundances clearly varied within the sequence of observations.

Regression analyses confirmed the generally positive relationship between ECa and earthworm abundances (Fig. 4). With ordinary linear regression, however, only 34% of variability of earthworm abundances could be explained with ECa (Fig. 4).

With state-space analysis, which considers the locations of observations (*Nielsen* and *Wendroth,* 2003), close relations between ECa and earthworm abundances could be identified. Earthworm abundance at location *i* was successfully estimated with earthworm abundance and ECa at location *i* – 1, even when only every second value of earthworm abundance was considered in the estimation. The missing values were interpolated (Fig. 5). In that case, 73% of variability of earthworm abundances could be estimated with every other value of earthworm abundances being interpolated by the model based on ECa. ECa contributed ≈ 23% of the estima-

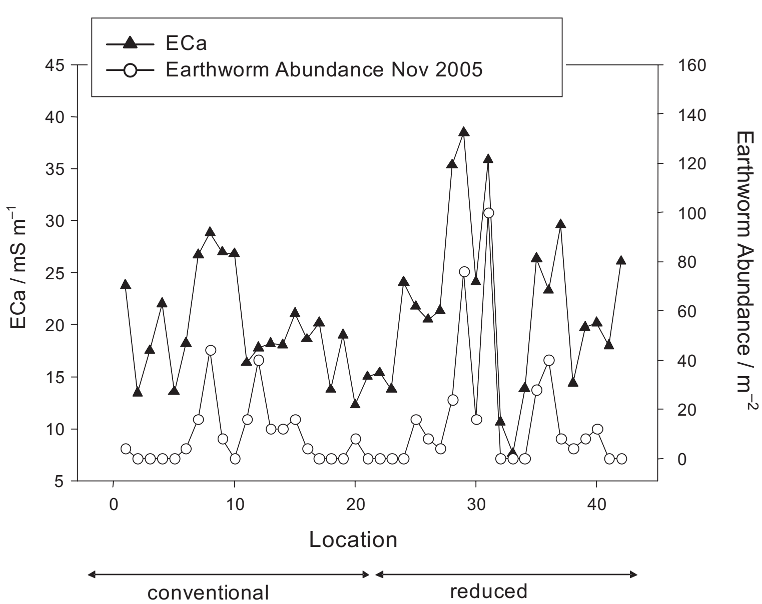


Figure 3: Apparent electrical conductivity (ECa) measured in May 2005 and earthworm abundance in November 2005 at 42 plots under conventional and reduced tillage.

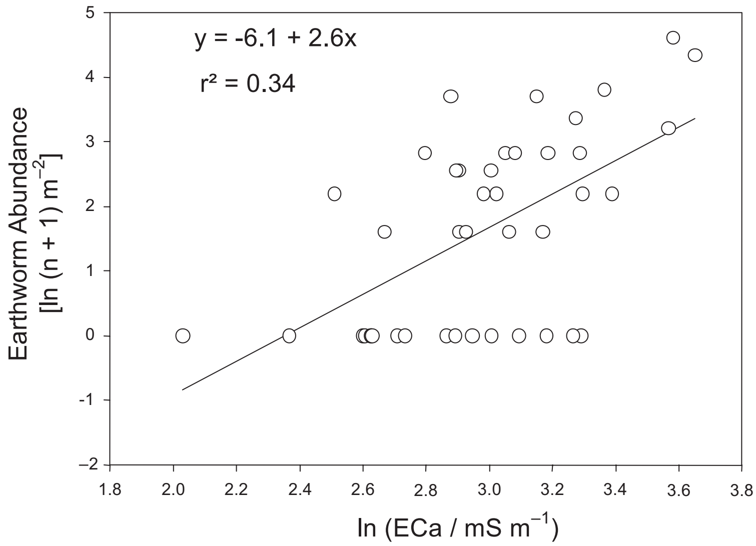


Figure 4: Linear-regression analysis of apparent electrical conductivity (ECa) and earthworm abundance in November 2005.

tion of the earthworm abundances along the data row as indicated by the transition coefficient in the state-space formula.

Differences between the tillage systems, with regards to the relationship between ECa and earthworms, were reflected in the width of the confidence interval of earthworm-abundance estimations (Fig. 5). The confidence interval was larger in the conventionally tilled side of the field, implying a larger uncertainty in estimations of earthworm abundance due to the less close relationships between ECa and earthworms (Fig. 5).

When only every third value of earthworm abundance was considered, an estimation of earthworm abundances based on ECa and earthworm abundances at preceding locations was no longer possible (data not shown). With this data base, no adequate state-space model was found which could interpolate the "missing" values of earthworm abundances in November 2005 based on the ECa values measured 6 months earlier.

4 Discussion

If close relations between ECa and earthworm abundances could be established, the apparent ECa, easily measurable in the field, could be helpful as a surrogate variable for time-consuming earthworm field assessments. We studied the relationship between field measured ECa and earthworm abundances in a 74 ha field on sandy soil, which was partly under reduced and partly under conventional tillage.

As hypothesized, ECa was positively related to soil texture and to earthworm abundances, indicated by the rank correla-

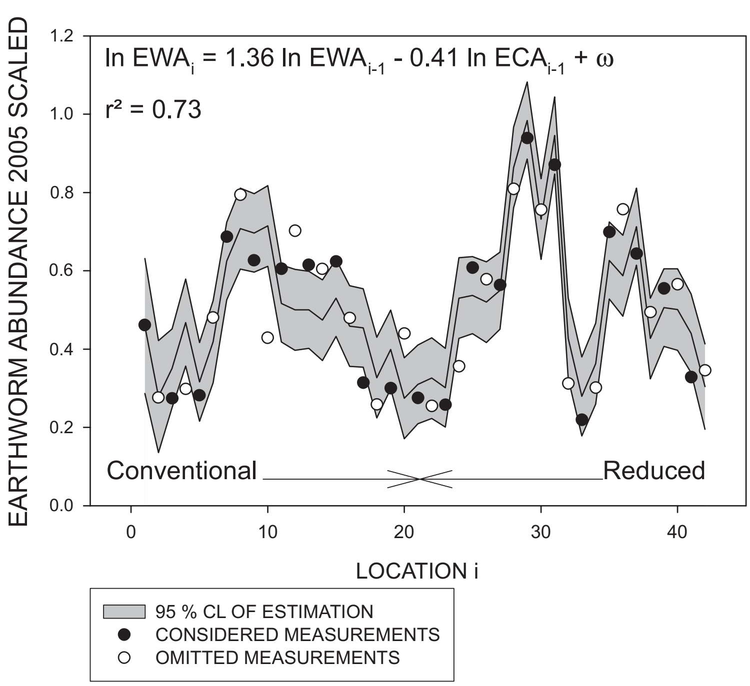


Figure 5: Estimation of earthworm abundances in November 2005 with ECa measured in May 2005, when every other value is omitted (state-space analysis, after *Nielsen* and *Wendroth*, 2003; CL = confidence limits); (EWA = earthworm abundance, ECa = apparent electrical conductivity).

tion coefficient between ECa values and earthworm abundances in 42 sampled plots and by the course of the spatial pattern of both variables along the sampled transects. The relationship between ECa and earthworm abundance, however, was not constant across the sequence of observations, but was influenced by the tillage system (Fig. 3). Rank correlation analysis showed close correlation between ECa and earthworm abundance in plots under reduced tillage as opposed to nonsignificant relationships in plots under conventional tillage.

What could be the reasons for this observation? The relationship between ECa and soil texture, *i.e.*, the fine-particles content, was closer in plots under reduced tillage indicated by the higher rank correlation coefficient (Tab. 2); the relationship between earthworm abundance and soil texture was also lower, albeit slightly, in plots under reduced tillage (Tab. 1). In other years and with other earthworm-abundance parameters, relationships between earthworms and soil texture had been considerably closer in plots under reduced tillage at the studied site (*Joschko* et al., 2009).

Yet, another possible reason for this result is the impact of conventional tillage on the ECa–texture and texture–earthworm relationship. This may have cancelled out any detectable relationship between ECa and earthworm abundance. Clearly, more information is needed about the relationship between earthworms and ECa measured in the field and about the tillage influence on this relationship. Interestingly, *Valckx* et al. (2006) reported a closer relationship between ECa and earthworm distributions in plowed, *i.e.*, conventionally tilled, soil; an observation, which is in clear contrast to our findings. Soil differences may be an explanation for this contradiction. The existence of soil differences certainly requires further research on that matter.

The question arises, how to deal with nonconstant relationships between variables in a sequence of observations. Due to the variability across the spatial sequence and the difference between the tillage systems, linear-regression analysis yielded a relatively low coefficient of determination when all plots were analyzed together (Fig. 4). In this case, a more promising approach is one that considers the spatial context of observations (*Wendroth* and *Nielsen,* 1994; *Nielsen* and *Wendroth,* 2003). Indeed, with state-space analysis, earthworm abundances along the spatial sequence could be estimated with earthworm abundances and ECa measurements at neighboring sampling locations (Fig. 5). This technique uses information from spatial covariances between different variables for the estimation of the variable of interest (*Nielsen* and *Wendroth,* 2003).

Our results further indicate that substitution of 50% of earthworm samples by geophysical measurements would still have yielded reliable results, provided that an alternate structure of sampled and nonsampled locations was chosen as experimental design (Fig. 5). Even when every other value of earthworm abundance was omitted during the analysis, a typical procedure to estimate the quality of state-space models (*Nielsen* and *Wendroth,* 2003), earthworm abundances were successfully estimated at “unsampled” locations. This constellation is in analogy to a field situation where only half of the plots are sampled for earthworms, whereas electrical-conductivity values are available for all plots or sample locations. Our data suggest, that earthworm abundance on every other plot can be estimated based on the earthworm abundance and apparent electrical conductivity at the preceding plot; ECa values at neighboring locations can be used for estimating earthworm abundances at “unsampled” locations. A further reduction of the number of “sampled” plots no longer yielded adequate state-space models. Thus, our results may be of practical importance for the future application of ECa as a surrogate variable for earthworm abundances in tilled soils.

Considering the spatial context for estimating earthworm abundance from ECa information is crucial since the relationship between ECa and earthworms differs along the sequence of plots, in our case induced by different tillage systems. With state-space analysis, it is possible to account for different levels of relationships between variables within a spatial series (*Wendroth* and *Nielsen,* 1994; *Nielsen* and *Wendroth,* 2003). Nonconstant relationships between variables are common in soils and landscapes (*Nielsen* and *Wendroth*, 2003).

Our results show that more research is needed for unravelling the relationship between ECa and earthworm abundance and soil texture in tilled soils. Also, further attention should be directed to the relationship between ECa and soil organic-C content, which is in general the second-most important state variable for earthworm distributions in the sandy soils studied (*Krück* et al., 2006; *Joschko* et al., 2009). Soil organic C is not well represented by the ECa measurements in soil under conventional tillage (Tab. 2). It is known from the literature that ECa is positively related to soil texture; the relationship to soil organic C, however, may be negative or totally absent (*Johnson* et al., 2001; *Chen* et al., 2004; *Siri-Prieto* et al, 2006). A different relationship between ECa and soil organic C in soil under conventional as opposed to reduced tillage has not been reported so far.

5 Conclusion

The apparent ECa obtained by field survey with a portable geoelectrical instrument was quantitatively related to earthworm abundances in tilled sandy soil. Our results from an on-farm field study with average distances of 70 m between sampling locations suggest that 50% of the earthworm samples may be substituted by ECa measurements when sampled and unsampled locations are alternating. Further research is needed to evaluate the potential of ECa measurements for predicting earthworm abundances in soil.

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