Effect of fertilizers and irrigation on multi-configuration electromagnetic induction measurements

M. S. Kaufmann[1]*, C. von Hebel[1], L. Weihermüller[1], M. Baumecker[2], T.Döring[2,3], K. Schweitzer[2], E. Hobley[4], S. L. Bauke[5], W. Amelung[1, 5], H. Vereecken[1], J. van der Kruk[1]

[1] Agrosphere (IBG-3), Institute of Bio- and Geosciences, Forschungszentrum Jülich GmbH, 52445 Jülich, Germany

[2] Department of Crop and Animal Sciences, Humboldt-Universität zu Berlin, 14195 Berlin, Germany

[3]Institute of Crop Science and Resource Conservation, Agroecology and Organic Farming, Auf dem Hügel 6, 53121 Bonn, University of Bonn, Germany

[4] Soil Science, TU München, Emil-Ramann-Straße 2, 85354 Freising, Germany

[5] Institute of Crop Science and Resource Conservation, Soil Science and Soil Ecology, Nussallee 13, 53115 Bonn, University of Bonn, Germany

***Corresponding author:** ma.kaufmann@fz-juelich.de

Running title: Soil treatment effects on EMI

Abstract

Electromagnetic induction (EMI) data are often used to investigate spatial and temporal patterns of soil texture, soil water content, and soil salinity. We hypothesized that the EMI methodology might thus also offer potential to detect agricultural legacy effects originating from fertilization and irrigation of different fields. Therefore, we performed EMI measurements at two long-term field experiments (LTFE) in Thyrow near Berlin (Germany) that differed in agricultural management with regard to long-term irrigation in combination with mineral (NPK and lime) and organic fertilization (straw and farmyard manure). Two different rigid-boom multi-coil EMI instruments were used to simultaneously measure the apparent electrical conductivity (ECa) over nine different depth ranges to study the entire soil profile from the topsoil to the deep subsoil. Additionally, soil samples were taken from the different treatments to ground-truth the measurements and disentangle the fertilization and/or irrigation effects from natural soil heterogeneity. The soil samples indicated a rather homogenous soil and the correlation between soil parameters/states were not significant. However, the treatments showed significant differences in measured ECa values. In general, ECa values were largest at regular irrigated as well as at mineral and organic fertilized plots, whereby regular irrigation exhibited the largest impact on EMI records even though the last irrigation was months before the EMI measurement. Overall, this study reveals that EMI data can support the classical in-situ assessment of agricultural management effects within LTFE, while offering new potentials in detecting and understanding legacy effects of agricultural management on spatial soil properties at farm level.

Keywords: Irrigation, fertilizer, electromagnetic induction, soil Mapping, electrical conductivity

Introduction

Long-term field experiments (LTFE) are well-suited to investigate short and long-term dynamics of the soil-plant system and its dependency on management practices (Dick, 1992). Typically, LTFEs maintain constant treatment conditions on the same plots over at least 20 years. Thus, treatment effects accumulate over time. Traditionally, the effects on soil properties are only measured in the plough horizon covering the uppermost 20 to 30 cm, partly because invasive subsoil sampling endangers the integrity of such LTFEs. Yet, there is increasing evidence that agricultural management and root growth alters the subsoil (e.g., Barej et al., 2014; Hobley et al., 2017; Kautz et al., 2013). Characterization of the full soil profile is therefore essential for understanding the whole soil-plant system. Almost all traditional techniques for subsoil investigation such as deep coring or soil pits are invasive, laborious, time-consuming, and of limited lateral resolution. In contrast, geophysical methods allow rapid and non-invasive mapping of proximate soil characteristics with relatively high lateral and vertical resolution.

Predominantly, data of non-invasive geophysical electromagnetic methods like electromagnetic induction (EMI) (e.g. Corwin and Lesch, 2005), electrical resistivity tomography (ERT) (e.g. Brunet et al., 2010), and ground penetrating radar (GPR) (e.g. Huisman et al., 2003) are able to highly resolve the upper few meters of soil. EMI measurements are particularly successful in estimating the spatial variability of soil properties or states like water content (e.g. Altdorff et al., 2017), soil texture (e.g., Huang et al. 2014), crop growth(e.g. Stadler et al., 2015), and soil salinity (e.g. Dakak et al., 2017). In general, soil properties or states are derived from regression equations between measured apparent electrical conductivity (ECa) and locally measured soil properties and/or states of interest. However, the obtained regression models are site-specific. As many soil characteristics can influence ECa simultaneously, a useful regression can only be derived when the influence on ECa of the soil properties and/or states under investigation is greater than the impact of other confounding factors.

For example, in the time frame and field sizes of LTFEs, we can distinguish stable and dynamic influences on ECa. Soil texture can be considered stable, whereas soil water content or pore water salinity change over time. Depending on the field and its mechanical management, bulk density is either static (in the subsoil) or dynamic (in the plough horizon). Puddling, for example, changes the bulk density and the soil compaction can lead to higher ECa (Islam et al., 2014). Therefore, fertilization, irrigation, or mechanical management affects the dynamic changes in the ECa signal, which can theoretically be disentangled from the static soil properties influencing ECa.

Fertiliser application introduces mineral and organic ions into the soil, which increases soil electrical conductivity. The influence of fertilization and irrigation as a key driver of ECa changes has, however, received little attention so far. Márquez Molina et al. (2014) spatially mapped the impact of cow manure, and its release of ions on a cattle field using EMI, and Eigenberg et al. (2002) showed that ECa was sensitive to different soil nutrient levels.

Similarly, ECa is strongly affected by water content and salinity (De Jong et al., 1979). Rhoades et al. (1999), for instance, used lower ECa values to identify parts of the field receiving less water during irrigation. Nevertheless, the effect of fertilization and irrigation on ECa is often neglected in interpreting regular EMI surveys, especially at the field or farm level. One reason is that the differences in fertilization and/or irrigation are commonly not known or have been assumed to play only a minor role. LTFEs offer a unique opportunity to investigate the combined effect of fertilization and irrigation on ECa, since managements are controlled and replicated over the long-term. Furthermore, EMI measurements provide information about the homogeneity of the experimental setup and help to systematically interpret differences in soil characteristics between field replicates (Rudolph et al., 2016).

Therefore, the objectives of this study are to evaluate the single and combined effects of irrigation and mineral and organic fertilization on ECa by mapping the lateral and vertical variability of the ECa at LTFEs. To achieve these goals, two rigid-boom multi-configuration EMI instruments were used providing in total nine different depth ranges of investigation (DOI) along with intensive ground truthing. One LTFE is used to study the effect of irrigation and different amounts of mineral fertilization on ECa. On the second LTFE, the impact of mineral and organic fertilization on ECa is studied. For this, the data of the nine shallow-to-deep sensing EMI coil configurations are statistically analysed. Firstly by regression of soil characteristic with ECa values and secondly by testing whether the mean ECa differ significantly in-between different treatments.

Material and methods

Field sites

The LTFEs are located at the Agricultural Research and Teaching Station at Thyrow of the Humboldt University of Berlin (Germany), approximately 25 km south of Berlin in the state of Brandenburg (52°15 N, 13°14 E, 44 m a.s.l.). Thyrow is situated on a ground moraine plateau, and the soil is classified as an Albic Luvisol (IUSS, 2006) consisting of sand, loamy sand, and sandy loam (Baumecker et al., 2009). Due to the overall sandy texture, the soils are characterized by low fertility and water holding capacity. The yearly average temperature is 9.2 C° with a relatively low annual precipitation of 510 mm with occasional drought periods between April and July (Ellmer et al., 2000). In this study, two fields receiving different fertilization and irrigation treatments were investigated (Figure 1).

D-I Static Irrigation and Fertilization Experiments

The long-term *Static Irrigation and Fertilizer Experiment* (D-I) was established in 1969 with the aim to study the effect of irrigation and increased mineral nitrogen fertilizer on the yields of different crops. The crop rotations are cocksfoot (*Dactylus glomerata L.*), potato (*Solanum tuberosum L.*), winter wheat (*Triticum aestivum L.*), oilseed rape (*Brassica napus L.*), and winter rye (*Secale cereale L*). In total, eight treatments (Table 1) were established in triplicates on plots of 9 x 5.5 m (black lines in Figure 1). Per plot, only the inner 5 x 4 m is considered for data interpretation to avoid border effects. The replicates were not randomized but allocated in rows next to each other. The amounts of applied nitrogen fertilizer were zero in the east and increased over normal (N1) toward excessive (N2) in the west. The application amount varied within crop rotation and was on average 82 N kg/ha for N1 and 154 N kg/ha for N2 using a standard calcium ammonium nitrate fertilizer (Trost et al., 2014). Except for the western N2 treatments, the rye and wheat stubbles were incorporated as organic fertilizer.

Due to occasional droughts in late spring and the low water holding capacity of the sandy soil, irrigation was introduced as a treatment in the southern half of the field in 1970. With a sprinkler system along the irrigation street (marked blue in Figure 1), local groundwater pumped from 15 m depth was irrigated with a yearly average of 98 mm (calculated with the irrigation control system BEREST (Schirach et al., 1988)). Groundwater analysis showed a pH of 7.7, an electrical conductivity of 88 mS/m and a mineral content of 122 Ca mg/l, 19 Na mg/l, 16 Mg mg/l, and 6 Si mg/l such that on average of ~ 0.2 kg/ha/year cations were introduced by irrigation. Additionally, the complete D-1 was fertilized with P (17.5 P kg/ha) and K (100 K kg/ha) and tilled conventionally.

D-IV Static Nutrient Deficiency Experiments

The long-term *Static Nutrient Deficiency Experiment* (D-IV) was established in 1936 to study the combined effects of mineral and organic fertilization on yields. In this setup, one control treatment received no fertilizer, while seven treatments were fertilized with different combinations of mineral fertilizer, i.e., nitrogen (N), phosphorus (P), potassium (K), lime, and/or farmyard manure (FYM) (see Table 2). For N, P, and K application rates were 90, 24, and 100 kg/ha and year, respectively. Liming was applied annually to obtain an optimum pH of 5.5 -5.8, whereas FYM was applied every second year with 30 t/ha on dry mass basis (Ellmer and Baumecker, 2005). Each treatment was replicated four times in a limited randomized setup on plots of 10 x 7.2 m (black lines in Figure 1). Here, only the inner 6 x 4 m are considered for data interpretation.

Soil Sampling and laboratory analysis

For the soil characterization, 22 and 24 soil cores were collected to a depth of one meter from the D-I and D-IV experiment, respectively, on the same days as the EMI measurements. All soil cores were divided into predefined depth intervals of 0-30, 30-50, 50-70, and 70-100 cm. The soil was additionally cut at 24 cm, and on D-I at 40 cm, and 59 cm due to visible soil horizons. The coring locations are shown in Figure 1, whereby not all properties and states were measured on all cores and at the same time, as the data were collected in the frame of the Soil³ collaborative project within the BONARES program (https://www.bonares.de). In both trials (D-I and D-IV), 11 out of the 16 treatments were sampled on all replicates. At D-I, six treatments were sampled, whereby the ‘N1+straw’ with and without irrigation was not sampled. At the D-IV trial, the treatments ‘no fertilizer,’ ‘NPK+lime,’ ‘NPK,’ ‘NK + lime,’ and ‘PK + lime’ treatments were sampled. In total, 226 soil samples of the treatments (magenta circles in Figure 1) were analysed for pH (in water with 1:5 w/v) [unit less], reference soil electrical conductivity ($EC_{1:5}$, mixture of

1 part soil and 5 parts distilled water) [mS/m], gravimetric soil water content (SWC, oven dried at 105 °C) [%], bulk density (BD, gravimetrically determined at oven- dried subsamples at 40 °C according to Bauke et al. (2018)) [g/cm^3], organic carbon content (OC, according to Hobley et al. (2018)) [%], and potential cation exchange capacity (CEC) [$cmol_c$/kg] was determined in sample percolate according to Thomas (1982). Cation concentrations in percolate were measured by atomic absorption spectroscopy (AAS; novAA 400P, Analytik Jena, Jena, Germany). CEC was measured for all samples on D-IV, and on D-I at one plot per treatment whereby only 130 out of the total 226 samples were analysed. The soil texture, i.e., clay (< 2µm), silt (2-63 µm), and sand (> 63 µm) [%], was analyzed only at selected complete profiles (stars in Figure 1) and at selected depth samples (cross in Figure 1).

Electromagnetic induction (EMI) survey

Electromagnetic induction (EMI) measures the apparent electrical conductivity (ECa) reflecting a weighted average value over the vertical electrical conductivity distribution within a certain depth range (Keller and Frischknecht, 1966). This depth range (Figure 2) depends mainly on the coil orientation and coil separation (*s*) (McNeill, 1996). Coils can be either oriented vertical co-planar (VCP), which results in more sensitivity to shallow soil depths, or horizontal co-planar (HCP) resulting in increased sensitivity at greater depths. Using a setup with both coil configurations provides both top- and subsoil information. Figure 2a shows the relative sensitivity curves for VCP and HCP orientation normalized to the coil separation (*s*). Hereby, the depth range of investigation (DOI) is defined as the depth up to which 70% of the relative response function accumulates, which is around 0.75 times *s* for VCP and 1.5 times *s* for HCP (McNeill, 1980).

The performed EMI survey used two different rigid-boom multi-configuration EMI instruments of different length, one operating in VCP and the other in HCP orientation. The CMD-

MiniExplorer (ME) was used in VCP mode, and a custom-made special edition (SE) was operated in HCP mode (both manufactured by GF-Instruments, Brno, Czech Republic). The measurement frequencies were 30 kHz for the ME and 25.17 kHz for the SE, respectively. The ME has three receiver coils (s = 32, 71, and 118 cm), while the SE has six coils (s = 35, 50, 71, 97, 135, and 180 cm), which provided a good coverage of the entire soil profile with complementary DOIs ranging from 0-0.25 m (ME 1 with VCP s = 32 cm) to 0-2.7 m (SE 6 with HCP s = 180 cm) depth.

For the EMI survey, the instruments were mounted on sledges to eliminate any influence of operator handling and to minimise changes in the instrument height above ground. The sledges were pulled 2 m behind a tractor at a speed of 5 km/h. Each measurement point was located with a single frequency GPS (Novatel, see Rudolph et al. (2018) for details) to account for positioning errors 0.5 m were added to the inner border of the treatment plots. The fields were measured in parallel lines with a spacing of approximately 1 m, passing each treatment at least three times. With a sampling rate of 10 Hz, an inline measurement every 0.25 m was taken, resulting in at least 50 measured ECa samples per plot and configuration. At D-I, the measurements were performed on 12th of April and D-IV on 15th of March 2016, both on bare soil before sowing.

EMI data processing and calibration

In a first step, ECa outliers (Minsley et al., 2012) were removed by a filtering strategy as suggested by von Hebel et al. (2014). As raw EMI measurements are often prone to systematic errors (e.g., Gebbers et al., 2009; Nüsch et al., 2010), they can only be interpreted qualitatively (Binley et al., 2015) . Hence, the EMI data were calibrated following the approach of Lavoué et al. (2010) by collocated EMI and electrical resistivity tomography (ERT) measurements along a transect (see transect location in Figure 1). For this calibration, the vertical electrical conductivity distribution from inverted ERT data are used as input in a Maxwell-based full-solution electromagnetic induction forward model (Wait, 1954) to predict ECa values of the used EMI instrument at each measurement position along the ERT transect. Based on the modeled ECa data, a linear regression was obtained resulting in configuration specific calibration equations, turning the raw ECa signal to quantitatively meaningful data (von Hebel et al., 2018; von Hebel et al., 2014). For both field trials, the ERT measurements were performed using a Syscal Pro resistivity meter (IRIS instruments, Orleans, France) on a 30 m transects with 120 electrodes (0.25 m electrode spacing) measured in Dipole-Dipole mode.

As the two fields were not measured on the same day, the EMI data were additionally standardized to a reference 25°C soil temperature by using the approach of Corwin and Lesch (2005). For this, the soil temperature recorded at 50 cm depth at a close by weather station (~300 m) was used. For visualisation, the ECa was interpolated using natural neighbours with a grid size of 1x1 m, whereas the non-interpolated but filtered data were used in the statistical analysis.

Statistical analysis

Each processed ECa value was assigned to the corresponding plot number, whereby ECa values outside of the inner plots were rejected. The influence of the different EMI configurations on treatment means was tested with a repeated measure ANOVA. Since no significant interaction was found, the nine EMI configurations were combined for further statistical analysis. As the ECa data were not normally distributed, the Mann–Whitney U-test for the analysis of the variance of the treatment means was applied, with a Kruskal–Wallis H-test used to identify significant differences between means at a probability of $p<0.05$. Additionally, the Pearson correlation coefficient r was used to describe the correlation between soil characteristics and interpolated ECa values. The corresponding tables to the statistical analysis can be found in the supporting information.

Results

Soil properties

Both trials were characterized by relatively low variability in soil texture (Figure 3 a & b). The sand fraction varied between 82 and 87% from the surface to a depth of 50 cm. Below 50 cm, the sand content decreased slightly to 70 to 79%. The silt content (12% -15%) remained relatively constant over depth. Conversely, the clay content varied between 6 to 7% and 10 to 16% in the top- and subsoil, respectively.

For BD, SWC, OC, $EC_{1:5}$, pH and CEC treatment means along with the standard deviations are plotted in Figure 3, and volumetric water content calculated from SWC and BD is shown in the supporting information. Depths, where at least two treatments differed significantly from another, have been marked with an asterisk. As can be seen, BD in the topsoil (0-24 cm) was similar in all treatments with values of 1.43 (D-I) and 1.6 g/cm (D-IV) due to soil tillage. On D-I, BD increased with depth to maximum values of 1.9 g/cm at 70 cm, and on D-IV to 1.8 g/cm with the maximum value of 2.0 g/cm at 50 cm, whereby a relatively large standard deviation was measured (no significant difference between the treatments). The variance in bulk density is possibly caused by undulating layers arising from the pedogenesis of the ground moraine (Baumecker et al., 2009).

At both field trials (D-I, D-IV), the SWC was similar (Figure 3 e &f), despite not being measured on the same day. The SWC increased from 6% in the topsoil to 12% in the deeper subsoil indicating a rather dry soil profile and even drier topsoil. Notably, no significant SWC differences (p<0.05) were present between the irrigated and non-irrigated plots. This we attribute to the length of time between the SWC analysis and the last irrigation event, which was performed in the previous summer, allowing profile water contents to equilibrate over the wetter winter period.

At both LTFE, OC content was low (<0.7%) coinciding with the sandy soil texture. The highest OC content was measured in the topsoil (0-30 cm) with small variations between the treatments (partly significant), decreased until 50 cm from where on OC content stayed stable (~ 0.06 %) without any variation between the treatments. At D-I, the non-irrigated and irrigated treatments N2+straw had significant higher topsoil OC content than the other treatments, which is in agreement to the observation, that N2+straw treatments showed the highest yields for non-irrigated and irrigated plots. However, the non-irrigated 'N2+straw' still showed lower yields compared to all irrigated treatments. Finally, OC contents were not dependent on irrigation, as the same fertilizer treatments with and without irrigation did not differ significantly in OC content, as also reported by Trost et al. (2014). At D-IV the treatment 'NPK' differed significantly from the treatment without fertilizer and 'PK + lime' (both only at 0-24 cm) corresponding to 85% and 40% lower yields (Ellmer et al., 2000). Even though, 'NPK+lime and 'NK+lime' had similar yields as 'NPK' (also higher OC content) no significant difference to the 'no fertilizer' treatment was present.

Measured soil $EC_{1:5}$ was low (< 10 mS/m) with large standard deviation. The highest values were measured in the plough layer and declined with increasing depth (Figure 3 g & h). As all treatments including the one with no fertilizer had a similar $EC_{1:5}$, the larger $EC_{1:5}$ in the topsoil were likely caused by the higher OC contents (r >0.5).

In contrast to all other soil characteristics, the pH showed significant differences between treatments overall depths (Figure 3 i & j). At the non-irrigated plots in D-I, the pH was < 7 (slightly acidic). At the irrigation treatment plots, the pH was 7-8 (neutral to slightly alkaline) in the topsoil and became with increasing depth more similar to the non-irrigated treatments < 7, whereas ‘straw+Ir.’ stayed neutral (around 7) until 70 cm. In the D-IV trial, two clear groups could be distinguished. Treatments without lime (no fertilizer and NPK) were in general acidic (pH < 6) with decreasing acidity to lower depths. The limed treatments showed a neutral to slightly alkaline pH of 6.5 -7.

In the sandy soil, with low variability in clay content and OC content within the measured depth layers, CEC (<6 $cmol_c$/kg) was low with only small variability. At both LTFE, the CEC varied with clay content changes over depth (r>0.6). At D-I only one sample per treatment was measured, and so no significance test was performed. The high variation of CEC below 50 cm can be attributed to small scale heterogeneity in soil texture. In the first 50 cm, no irrigation effect on CEC was detectable. At D-IV, a difference in CEC between the non-fertilized reference and the fertilized treatments with slightly lower CEC in the reference was found up to 70 cm depth (significant until 30 cm, see supporting data). Even though OC content has a large impact on CEC, only a weak correlation between OC content and CEC was found (r < 0.3 at 0-30 cm).

Electromagnetic induction measurements

After data processing, approximately 20.000 calibrated ECa values were available for all nine EMI configurations. In general, low ECa values between 0.5 and 5 mS/m were obtained for both trials (Table 3), which is consistent with the dry sandy soil at time of measurement. At each interpolated grid, the nine different EMI configuration showed only small ECa differences (mean standard deviation of 0.2 mS/m between the configurations), indicating that the small variation of clay content with depth is rarely affecting the overall EMI signal.

Figure 4b shows the interpolated ECa values for one EMI configuration (SE 3: HCP; s = 71 cm), which corresponds to an approximate DOI of 0-1 m and Figure 4c shows the averaged and border buffered ECa of each treatment of that SE 3. As can be seen, the southern part, which has been irrigated since 1970, clearly showed elevated ECa values of up to 5 mS/m relative to the non-irrigated northern part with ECa values around 3 mS/m. The effect of the different fertilization rates could not be detected clearly in the ECa pattern for this EMI configuration. The mean ECa values for each treatment (Figure 4c) revealed the same pattern. These relationships were similar for all nine EMI configurations and clearly indicated a legacy irrigation effect on ECa data.

The same analysis was performed to analyse the fertilization legacy of the *static nutrient deficiency experiments*, D-IV. More complex EMI maps as shown in Figure 5 (EMI configuration SE 4: HCP; s = 97 cm and a DOI of 0-1.5 m) were measured. This we attribute to the randomization of the trial, which increased spatial ECa variability at the trial. Nevertheless, clear similarities in the mosaic pattern between the treatments (Figure 5a) and the mean ECa values (Figure 5c) were evident. For example, lowest ECa values (~ 2 mS/m) were observed in the non-fertilized plots, reflecting the natural soil background, whereas the full fertilization of 'FYM/NPK +lime' showed the highest ECa with ~5 mS/m. The other management practices had intermediate ECa values. Once again, the results were similar for all nine EMI configurations, indicating the influence of fertilization effects on EMI data.

Correlation between soil characteristic and ECa

The influence of the different soil characteristics on the ECa values was tested by the strength of correlation between the soil properties of both experiments with the corresponding EMI measurements, whereby each one of the nine EMI configurations was regressed to the single soil characteristics measured at each depth (see supporting information). Topsoil SWC (0-24 cm) and

CEC (0-30 cm) showed a significant moderate relationship with an $r = 0.44$-0.70, whereas for the SWC at larger depth (24-100 cm), CEC (30-100 cm), OC, BD, $EC_{1:5}$, and soil texture the correlation with ECa was weak ($r < 0.4$), and for pH (0-70 cm) and ECa a moderate significant relationship of $r = 0.35$-0.6 (varying for each EMI configuration) was found.

Statistical analysis of treatment effect on EMI

To analyze the treatment effect on ECa more quantitatively, we performed a statistical analysis of the data. In Figure 6, boxplots are presented, where the ECa values of the nine EMI configurations are shown together along with the mean ECa (μ) and the standard deviation (mS/m). Additionally, the mean ECa of the individual plots for each treatment is represented as dots. Note that in D-IV there are four plots per treatment compared to the three replicates in D-I. Additionally, different lower case letters indicate significant differences between the treatments ($p<0.05$) (see supporting information).

For the D-I trial, the four left-hand panels of Figure 6a show the non-irrigated treatments, where ECa was around 3 mS/m, with no statistically significant difference between the treatments. There was, however a trend to an approximately 15% smaller ECa in the treatment without straw. The four right panels of Figure 6 show the ECa measured in the irrigated plots, with values of 3.5 to ~ 5 mS/m, the ECa was significantly higher than those in the non-irrigated plots. The ECa was largest for the 'straw +Ir.' treatment (4.5 mS/m) and decreased slightly with the addition of mineral N fertilizer. Within the four treatments only 'straw +Ir.' and 'N2 + Ir.' differed significantly. Similar to the non-irrigated treatments omitting straw decreased the ECa by ~15%.

A direct comparison of the irrigated and non-irrigated treatments revealed a significant increase in ECa of around 30%, as well as a larger standard deviation in the irrigated treatments and significant differences between irrigated and non-irrigated plots.

The fertilization trial D-IV allows investigating the fertilization legacy on ECa (Figure 6b). The control treatment had the lowest ECa of 2.8 mS/m, and the ‘FYM/NPK+lime’ treatment had the highest mean ECa with an increase of 53% compared to the control. All other treatments differed significantly from these two extremes and had intermediate ECa (up to + 26% compared to the control). Among the treatments with different deficiency of mineral fertilization, only ‘NK + lime’ differed significantly from the treatment only receiving FYM. The treatment ‘NK + lime’ was the only lime treatment differing significantly from the treatment with organic fertilizer without lime (‘NPK’). Even if in the other treatments the effect of liming was not significant, lime increased the ECa values by 4%.

Discussion

Soil characteristics and their relationship to ECa

Overall, the analysis of all 226 soil samples indicated a rather homogeneous soil in the vertical direction as reflected by the ECa values of the nine configurations. At all soil sample locations, similar soil texture, SWC, BD, $EC_{1:5}$, CEC, and OC content with low variability (mostly not significant) between the treatments were observed, explaining the low *r*-values between soil characteristic and measured ECa. This further implies that none of the soil properties/states alone can describe the ECa changes. For example, the topsoil SWC and CEC (moderate relationship to ECa) had a low variability (less than 1.2 % and 0.7 $cmol_c/kg^3$, respectively) and except for the CEC of the non-fertilized treatment, no significant difference between treatments in the soil parameter matching with the statistical analysis of EMI data was found. The weak relationship between ECa and $EC_{1:5}$ in our low saline soils can be possibly explained by other current conducting factors dominating the soil response to EMI as also stated by Rhoades et al. (1999).

Similar to other studies (e.g., Colburn, 1999; Lund et al., 1999) a moderate to strong relationship between pH and ECa was observed. The significant pH treatment differences between irrigated and non-irrigated plots (D-I) and limed to non-limed plots (D-IV) showed that pH values were respectively influenced by the irrigated groundwater and limeing. However, the relationship between pH and ECa is complex. As suggested by Adamchuk et al. (2004), the combination of pH and ECa measurements could be used to identify variable rates of lime applications.

Treatment effects EMI D-I

The main dominant legacy effect on D-I, the irrigation increased ECa by ~30%. Since the measured SWC of the non-irrigated and irrigated treatments were similar during the EMI survey, the increase in ECa is caused by using electrically conductive (88 mS/m) groundwater for irrigation, since the electrical conductivity of rainwater is in general much lower (Ayers, 1985). In a similar long-term irrigation study on sandy soil, Tarchouna et al. (2010) found a higher amount of exchangeable cations in irrigated soils, which would explain the increase of ECa.

Among irrigated plots those furthest away from the irrigation street used for the sprinklers (orange dots in Figure 6a, North) have significantly lower mean ECa values than the other two plots of the same treatments (South), whereas no significant differences were detected for the SWC, $EC_{1:5}$, and pH values between northern and southern plots (supporting information). Additionally, no clear trend to higher or lower BD in the north faced irrigated plots was present. As a consequence, the lower ECa was probably caused by receiving less water during irrigation, either caused by wind drift and /or by being further away from the sprinkler as also reported by Dechmi et al. (2003).

The observed decrease of ECa with the addition of N fertilizer at the irrigated plots correlates with higher yields of 16% for ‘N1+straw + Ir.’ and about 20% for ‘N2+(straw)+Ir.’ compared to

'Ir+straw' (Trost et al., 2014). According to Garabet et al. (1998) plants have an improved root growth and nitrogen uptake when irrigated, leading to higher biomass consuming more water from the root zone (Gonzalez-Dugo et al., 2010). In consequence, the higher water uptake might reduce the irrigation effect on the ECa data.

Omitting straw decreased the ECa by 15% in the irrigated and non-irrigated parts, suggesting a decreased release of ions in the absence of straw as also shown by Zavalloni et al. (2011).

Treatment effects on EMI D-IV

On D-IV fertilization legacy effects were evidently detected. In general, the increase of ECa with mineral fertilizer can be explained by the addition of ions to the soil - the higher the amount of fertilizer, the higher the ECa (Smith and Doran, 1996). The effect of N, P, or K deficiency on ECa values were negligible, explainable by low application amounts (kg per ha) compared to manure or lime application (up to few tons per ha). The slight increase of ECa with lime suggested that lime stabilizes the ions in the soil leading to higher ECa (Haynes and Naidu, 1998).

Almost no difference in ECa between organic fertilization and similar amounts of mineral fertilization indicated that mineral or organic fertilizers exhibited a similar impact on ECa. FYM enriches the soil in organic matter (OM), thus providing a solid-liquid phase for exchangeable cations (Corwin and Lesch, 2005) and continuous FYM application increases the soil salinity (Hao and Chang, 2003), leading to higher ECa. Additionally, both FYM based treatments indicated the largest variability in ECa, which likely reflects the difficulties of homogeneous manure application and incorporation into the soil, as well as potential differences in manure quality.

Toward management zone applications

Over both trials, five main management zones were visually and statistically recognized even though the ECa changes in between the treatments were ~ 2 mS/m only. On D-I the management zones irrigated and non-irrigated and on D-IV the three management zones non-fertilized, mineral or organic fertilization and mineral and organic fertilization were delineated. The study shows that on fields with homogeneous soil, EMI measurements can be used to identify zones with different amounts of irrigation and fertilization, which helps farmers managing the field zones. However, on heterogeneous fields, a single EMI measurement is insufficient to predict soil properties and management zones at the same time (Adamchuk et al., 2004). For this, a combination of soil samples, other measurements or time-lapse EMI measurements offer high potential in precision agriculture.

Conclusion

The results obtained at the two long-term field experiment sites indicate that irrigation and fertilization management exhibit a legacy effect on the soil ECa measured with EMI since no other soil property could explain the observed ECa variability. The lowest ECa values were measured at the control plots without treatment, which corresponds to the stable soil ECa background. Irrigation (for 47 years) induced a detectable legacy effect on the ECa values at the irrigated parts of D-I, where an increase of ECa up to 30% was caused by using groundwater for irrigation. Long-term fertilization legacy also significantly influenced EMI measurements, with effects most pronounced (+53%) under trials receiving farmyard manure in addition to high mineral fertiliser and lime application rates. In plots receiving lower fertilization rates, effects were smaller but were still considerable (26%). These results show the importance of considering different agricultural management legacy effects when interpreting ECa values in terms of soil properties in addition to the usual temporal stable and dynamic influences. Furthermore, our results reveal that multi-coil EMI measurements can be used to elucidate the homogeneity of agricultural treatments at LTFE's, as well as to investigate the uniformity of fertilization and irrigation applications.

Acknowledgment

This study was funded by BMBF: 'BONARES,' project Soil^3 (grant 031B0026C), logistically supported by TERENO, ACROSS, and TR32. We acknowledge Elisabeth Verweij, Luka Kurnjek, Michael Lesch, and Trung Hieu Mai for the help in the field and laboratory and thank the anonymous reviewers for significantly improving the manuscript.

References

Adamchuk, V. I., Hummel, J. W., Morgan, M. T., and Upadhyaya, S. K. (2004). On-the-go soil sensors for precision agriculture. *Computers and Electronics in Agriculture* **44**, 71-91.

Altdorff, D., von Hebel, C., Borchard, N., van der Kruk, J., Bogena, H. R., Vereecken, H., and Huisman, J. A. (2017). Potential of catchment-wide soil water content prediction using electromagnetic induction in a forest ecosystem. *Environmental Earth Sciences* **76**, 111.

Ayers, R. S. (1985). "Water quality for agriculture," FAO and UN.

Barej, J. A. M., Patzold, S., Perkons, U., and Amelung, W. (2014). Phosphorus fractions in bulk subsoil and its biopore systems. *European Journal of Soil Science* **65**, 553-561.

Bauke, S., von Sperber, C., Tamburini, F., Gocke, M., Honermeier, B., Schweitzer, K., Baumecker, M., Don, A., Sandhage-Hofmann, A., and Amelung, W. (2018). Subsoil phosphorus is affected by fertilization regime in long-term agricultural experimental trials. *European Journal of Soil Science* **69**, 103-112.

Baumecker, M., Ellmer, F., and Köhn, W. (2009). Statischer Nährstoffmangelversuch Thyrow. Dauerfeldversuche in Brandenburg und Berlin. Beiträge für eine nachhaltige landwirtschaftliche Bodennutzung. Potsdam, Germany: Ministerium für Ländliche Entwicklung. *Umwelt und Verbraucherschutz*.

Binley, A., Hubbard, S. S., Huisman, J. A., Revil, A., Robinson, D. A., Singha, K., and Slater, L. D. (2015). The emergence of hydrogeophysics for improved understanding of subsurface processes over multiple scales. *Water Resour Res* **51**, 3837-3866.

Brunet, P., Clement, R., and Bouvier, C. (2010). Monitoring soil water content and deficit using Electrical Resistivity Tomography (ERT) - A case study in the Cevennes area, France. *Journal of Hydrology* **380**, 146-153.

Colburn, J. W. (1999). Soil Doctor Multi-Parameter, Real-Time Soil Sensor and Concurrent Input Control System. *In* "Precision Agriculture" (P. C. Robert, R. H. Rust and W. E. Larson, eds.), pp. 1011-1021. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI.

Corwin, D. L., and Lesch, S. M. (2005). Apparent soil electrical conductivity measurements in agriculture. *Computers and Electronics in Agriculture* **46**, 11-43.

Dakak, H., Huang, J., Zouahri, A., Douaik, A., and Triantafilis, J. (2017). Mapping soil salinity in 3-dimensions using an EM38 and EM4Soil inversion modelling at the reconnaissance scale in central Morocco. *Soil Use and Management* **33**, 553-567.

De Jong, E., Ballantyne, A., Cameron, D., and Read, D. (1979). Measurement of apparent electrical conductivity of soils by an electromagnetic induction probe to aid salinity surveys. *Soil Science Society of America Journal* **43**, 810-812.

Dechmi, F., Playan, E., Cavero, J., Faci, J. M., and Martinez-Cob, A. (2003). Wind effects on solid set sprinkler irrigation depth and yield of maize (Zea mays). *Irrigation Science* **22**, 67-77.

Dick, R. P. (1992). A review: long-term effects of agricultural systems on soil biochemical and microbial parameters. *Agriculture, Ecosystems & Environment* **40**, 25-36.

Eigenberg, R., Doran, J. W., Nienaber, J. A., Ferguson, R. B., and Woodbury, B. (2002). Electrical conductivity monitoring of soil condition and available N with animal manure and a cover crop. *Agriculture, ecosystems & environment* **88**, 183-193.

Ellmer, F., and Baumecker, M. (2005). (Static nutrient depletion experiment Thyrow. Results after 65 experimental years). *Archives of Agronomy and Soil Science* **51**, 151-161.

Ellmer, F., Peschke, H., Kohn, W., Chmielewski, F. M., and Baumecker, M. (2000). Tillage and fertilizing effects on sandy soils. Review and selected results of long-term experiments at Humboldt-University Berlin. *Journal of Plant Nutrition and Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde* **163**, 267-272.

Garabet, S., Ryan, J., and Wood, M. (1998). Nitrogen and water effects on wheat yield in a Mediterranean-type climate. II. Fertilizer-use efficiency with labelled nitrogen. *Field Crops Research* **58**, 213-221.

Gebbers, R., Lück, E., Dabas, M., and Domsch, H. (2009). Comparison of instruments for geoelectrical soil mapping at the field scale. *Near Surface Geophysics* **7**, 179-190.

Gonzalez-Dugo, V., Durand, J. L., and Gastal, F. (2010). Water deficit and nitrogen nutrition of crops. A review. *Agronomy for Sustainable Development* **30**, 529-544.

Hao, X., and Chang, C. (2003). Does long-term heavy cattle manure application increase salinity of a clay loam soil in semi-arid southern Alberta? *Agriculture, Ecosystems & Environment* **94**, 89-103.

Haynes, R. J., and Naidu, R. (1998). Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutrient Cycling in Agroecosystems* **51**, 123-137.

Hobley, E., Baldock, J., Hua, Q., and Wilson, B. (2017). Land-use contrasts reveal instability of subsoil organic carbon. *Global Change Biology* **23**, 955-965.

Hobley, E., Steffens, M., Bauke, S. L., and Kögel-Knabner, I. (2018). Hotspots of soil organic carbon storage revealed by laboratory hyperspectral imaging. *Scientific Reports* **8**, 13900.

Huisman, J., Hubbard, S., Redman, J., and Annan, A. (2003). Measuring soil water content with ground penetrating radar. *Vadose zone journal* **2**, 476-491.

Islam, M. M., Meerschman, E., Saey, T., De Smedt, P., De Vijver, E. V., Delefortrie, S., and Van Meirvenne, M. (2014). Characterizing Compaction Variability with an Electromagnetic Induction Sensor in a Puddled Paddy Rice Field. *Soil Science Society of America Journal* **78**, 579-588.

IUSS, W. (2006). World reference base for soil resources 2006. *World Soil Resources Reports* **103**.

Kautz, T., Amelung, W., Ewert, F., Gaiser, T., Horn, R., Jahn, R., Javaux, M., Kemna, A., Kuzyakov, Y., Munch, J. C., Patzold, S., Peth, S., Scherer, H. W., Schloter, M., Schneider, H., Vanderborght, J., Vetterlein, D., Walter, A., Wiesenberg, G. L. B., and Kopke, U. (2013). Nutrient acquisition from arable subsoils in temperate climates: A review. *Soil Biology & Biochemistry* **57**, 1003-1022.

Keller, G., and Frischknecht, F. (1966). Electrical Methods in Geophysical Prospecting, International Series of Monographs in Electromagnetic Waves, vol. 10. Pergamon Press, New York.

Lavoué, F., Van Der Kruk, J., Rings, J., André, F., Moghadas, D., Huisman, J., Lambot, S., Weihermüller, L., Vanderborght, J., and Vereecken, H. (2010). Electromagnetic induction calibration using apparent electrical conductivity modelling based on electrical resistivity tomography. *Near Surface Geophysics* **8**, 553-561.

Lund, E. D., Colin, P. E., Christy, D., and Drummond, P. E. (1999). Applying Soil Electrical Conductivity Technology to Precision Agriculture. *In* "Precision Agriculture" (P. C. Robert, R. H. Rust and W. E. Larson, eds.), pp. 1089-1100. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI.

Márquez Molina, J. J., Sainato, C. M., Urricariet, A. S., Losinno, B. N., and Heredia, O. S. (2014). Bulk electrical conductivity as an indicator of spatial distribution of nitrogen and phosphorous at feedlots. *Journal of Applied Geophysics* **111**, 156-172.

McNeill, J. (1980). Electromagnetic terrain conductivity measurement at low induction numbers. Geonics Limited Ontario, Canada.

McNeill, J. (1996). "Why doesn't Geonics Limited build a multi-frequency EM31 or EM38?," Geonics.

Minsley, B. J., Smith, B. D., Hammack, R., Sams, J. I., and Veloski, G. (2012). Calibration and filtering strategies for frequency domain electromagnetic data. *Journal of Applied Geophysics* **80**, 56-66.

Nüsch, A.-K., Dietrich, P., Werban, U., Behrens, T., and Prakongkep, N. (2010). Acquisition and reliability of geophysical data in soil science. *In* "19th World Congress of Soil Science", pp. 21-24.

Rhoades, J. D., Corwin, D. L., and Lesch, S. M. (1999). Geospatial measurements of soil electrical conductivity to assess soil salinity and diffuse salt loading from irrigation. *GEOPHYSICAL MONOGRAPH-AMERICAN GEOPHYSICAL UNION* **108**, 197-216.

Rudolph, S., Marchant, B. P., Weihermüller, L., and Vereecken, H. (2018). Assessment of the position accuracy of a single-frequency GPS receiver designed for electromagnetic induction surveys. *Precision Agriculture*.

Rudolph, S., Wongleecharoen, C., Lark, R. M., Marchant, B. P., Garré, S., Herbst, M., Vereecken, H., and Weihermüller, L. (2016). Soil apparent conductivity measurements for planning and analysis of agricultural experiments: A case study from Western-Thailand. *Geoderma* **267**, 220-229.

Schirach, F., Wenkel, K.-O., and Germar, R. (1988). Sprinkling recommendations for practice in usig the systems IBSB-2 and BEREST. *Gartenbau (German DR)*.

Smith, J., and Doran, J. (1996). Measurement and use of pH and electrical conductivity for soil quality analysis. *In* "Methods for assessing soil quality", Vol. 49. Soil Science Society of America Madison, WI.

Stadler, A., Rudolph, S., Kupisch, M., Langensiepen, M., van der Kruk, J., and Ewert, F. (2015). Quantifying the effects of soil variability on crop growth using apparent soil electrical conductivity measurements. *European journal of agronomy* **64**, 8-20.

Tarchouna, L. G., Merdy, P., Raynaud, M., Pfeifer, H. R., and Lucas, Y. (2010). Effects of long-term irrigation with treated wastewater. Part I: Evolution of soil physico-chemical properties. *Applied Geochemistry* **25**, 1703-1710.

Thomas, G. W. (1982). Exchangeable cations. *Methods of soil analysis. Part 2. Chemical and microbiological properties*, 159-165.

Trost, B., Ellmer, F., Baumecker, M., Meyer-Aurich, A., Prochnow, A., and Drastig, K. (2014). Effects of irrigation and nitrogen fertilizer on yield, carbon inputs from above ground harvest residues and soil organic carbon contents of a sandy soil in Germany. *Soil Use and Management* **30**, 209-218.

von Hebel, C., Matveeva, M., Verweij, E., Rademske, P., Kaufmann, M. S., Brogi, C., Vereecken, H., Rascher, U., and van der Kruk, J. (2018). Understanding soil and plant interaction by combining ground-based quantitative electromagnetic induction and airborne hyperspectral data. *Geophysical Research Letters* **45**, 7571-7579.

von Hebel, C., Rudolph, S., Mester, A., Huisman, J. A., Kumbhar, P., Vereecken, H., and van der Kruk, J. (2014). Three-dimensional imaging of subsurface structural patterns using quantitative large-scale multiconfiguration electromagnetic induction data. *Water Resources Research* **50**, 2732-2748.

Wait, J. R. (1954). Mutual coupling of loops lying on the ground. *Geophysics* **19**, 290-296.

Zavalloni, C., Alberti, G., Biasiol, S., Vedove, G. D., Fornasier, F., Liu, J., and Peressotti, A. (2011). Microbial mineralization of biochar and wheat straw mixture in soil: A short-term study. *Applied Soil Ecology* **50**, 45-51.