Author Final Responses for:

Improving the relationship between soil texture and large-scale electromagnetic induction surveys using a direct current electrical resistivity calibration.

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Reviewer 2

Red Text – Author Response

The paper addresses a very important issue and tries to make a step forward towards a quantitative use of EMI data for soil characterization. Yet I have found the paper content very weak, for a number of reasons that I try and list below. In particular, there is a clear lack of consideration for the spatial scale of measurements – EMI, ERT, cores, lab samples – that hinders any further serious understanding of the different results that emerge from the study: indeed above and beyond the attempt to correct the EMI inversion on the basis of ERT data – considered as "ground truth".

Spatial scale between the EMI, ERI, cores, and lab samples.

After responding to each comment, the scale between EMI, ERI, cores, and lab samples is essential for explaining the outputs of this research. The ideal section for this to be included is Section 3.1 The calibration-inversion-comparison (CIC) framework. We choose point pairs for comparison (e.g., EMI and ERI conductivity) based on a distance from a target location. We should state that we upscale the core-based soil texture for comparison with the 3 closest EMI measurement locations, which was usually <3 m away in the (x,y) direction and < 0.5 m in the z direction. There should be a note on the limitations of this approach as well. The primary limitation is the unknown representative elementary volume for each method that may propagate uncertainty into the final interpretation.

Based on your second general comment, I have changed the term ‘calibration’ to ‘conditioned’. Calibration usually considers the reference models to be developed using a quantitative measurement (in our case inverted ERI conductivity) that will correct a second measurement (EMI). We acknowledge the ERI is not a quantitative measure of the soil properties and requires ‘ground truthing’ to validate any relationship developed between the ERI conductivity models and the relevant soil properties. As such, this does not limit the utility of the ERI conductivity models to improve the relationship between the EMI inverted conductivity models.

I will improve the language in the manuscript to strongly emphasize the ERI is not assumed to be the true earth model. Furthermore, I will state that a linear-regression based calibration is only conditioning the EMI data (i.e, scaling and shifting). The linear-regression based conditioning scales and shifts the EMI measurements to closely match the ERI conductivity ranges and seems to suppress noise in the EMI measurements by enforcing data to the regression line. I appreciate your comment and I believe there is a need to shift the language from calibration to conditioning will aid in the confidence of the outputs.

Here below are a number of comments:

(1): Table 1: The definition of sigma_a,sim (inv) is unclear: are we talking of the inverted EMI conductivity from calibrated or non-calibrated apparent conductivity data? (the whole thing is a bit obscure)

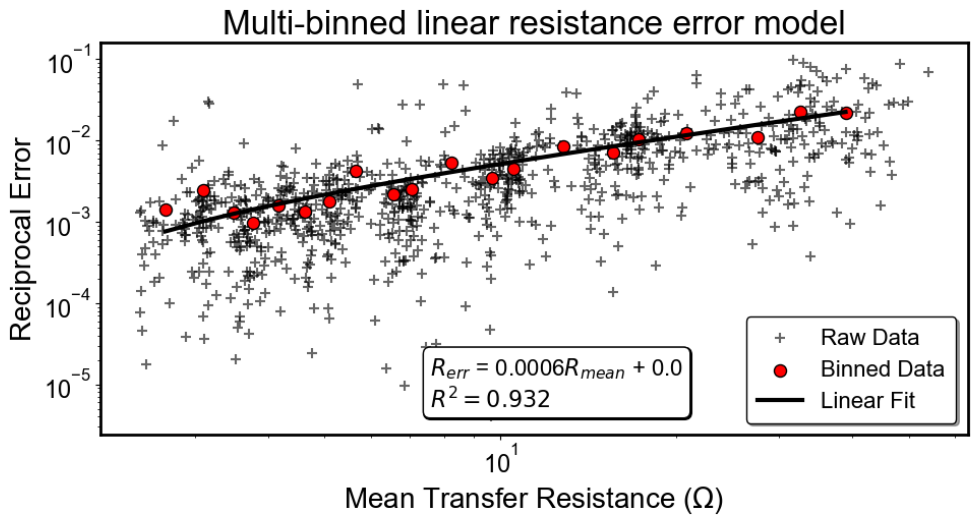
I agree the definitions are challenging to interpret. I have updated the table to make the variable definitions clearer. Additionally, I have changed ‘calibration’ to ‘conditioning’.

Variable	Definition
$\sigma_{a,\ EMI}[nc]$	EMI measurements without ERI conditioning
$\sigma_{a,\ EMI}[c]$	EMI measurements with ERI conditioning
$\sigma_{EMI}[nc]$	Inverted EMI conductivity without ERI measurement conditioning
$\sigma_{EMI}[c]$	Inverted EMI conductivity with ERI measurement conditioning
$\sigma_{a,\ sim}[cal]$	Simulated EMI apparent conductivity informed by inverted ERI conductivity for conditioning
$\sigma_{a,\ sim}[inv]$	Simulated EMI apparent conductivity derived from inverted EMI conductivity for EMI model evaluation
$\sigma_{ERI}[cal]$	Inverted ERI conductivity used to simulate $\sigma_{a,\ sim}[cal]$
$\sigma_{ERI}[val]$	Inverted from ERI conductivity used to validate σ_{EMI}[c]

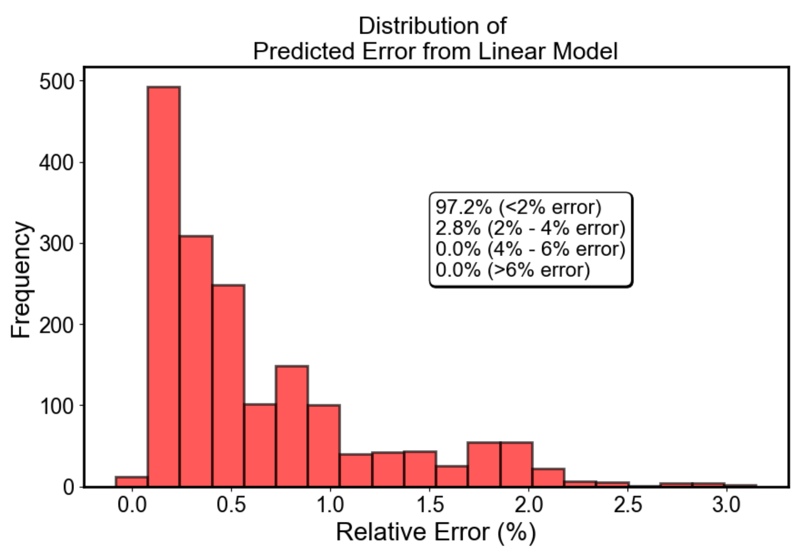
(2) Too much confidence on ERT – ERI as the authors name it – with no concern for the uncertainty concerning the ERT inversion itself.

We did consider the ERI uncertainty; however, this information was not provided in the manuscript. In the next revision, I will ensure that the inversion statistics regarding uncertainty is addressed.

1. Reciprocal Error Analysis (Line 170 in manuscript)

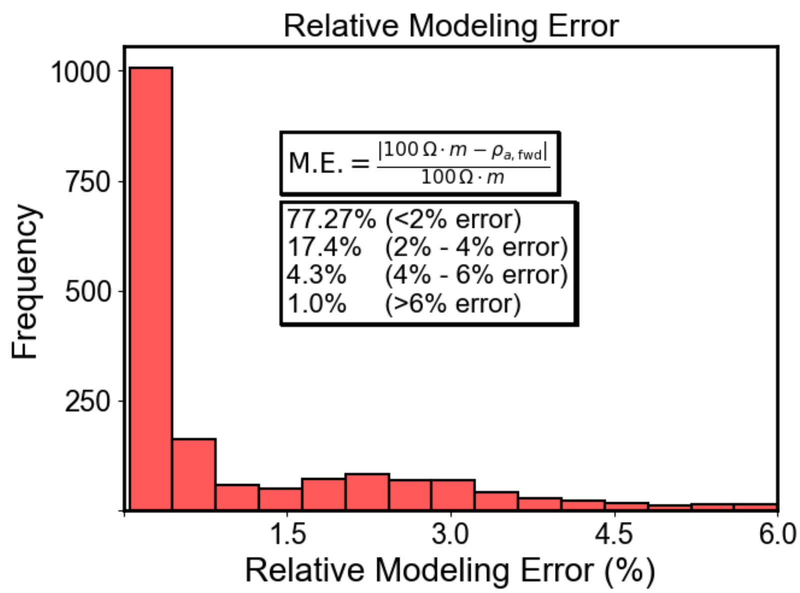


The multi-binned linear resistance error model defines a slope and intercept that is used to estimate errors for individual measurements. From the error model above, we can use a histogram of the relative error applied to see the distribution of likely errors for all measurements. The graph below indicates 97.2% of the data has a relative error of less than 2%.



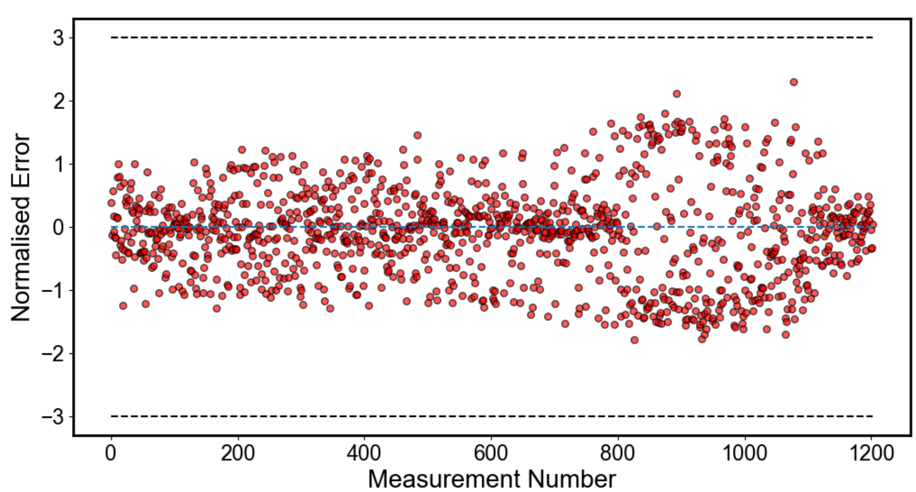
2. Modeling Errors

We also considered the modeling error from the mesh and measurement design. An ERI forward model is created whereby every element has a resistivity of 100 Ohm.m. The sequence of measurements (e.g., dipole dipole) is used to simulate a 100 Ohm.m resistivity model. The percent difference (using the equation in the graph below) provides information of the errors introduced by the sequence of measurements and the model discretization. Note M.E. in the equation is modeling error, $\rho_{a,fwd}$ is the simulated apparent conductivity measurements from the sequence of measurements.

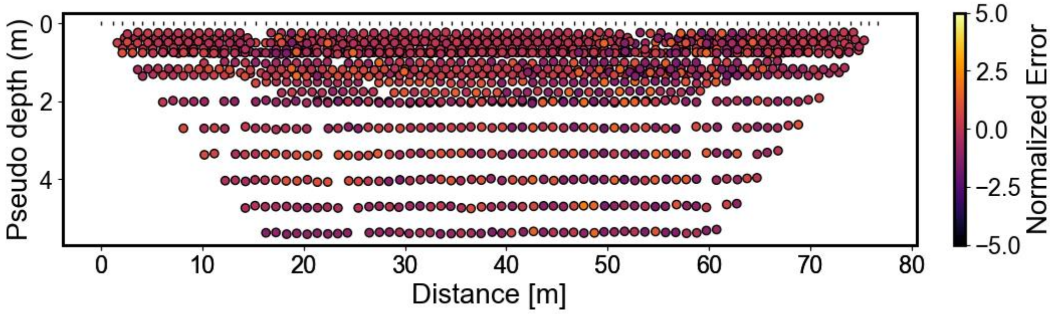


3. Normalized inversion errors

Normalized inversion errors, defined as the data misfit divided by the standard deviation, were also assessed which is between the data and simulated measurements produced from the final conductivity model for the inversion. The spatial distribution of the normalized error shows the error is homogeneous across each of the profiles.



We also evaluated the spatial variation of the normalized error with the pseudo section below.



(3) The authors attribute the (strong) discrepancy between EMI-derived sigma sections and the ERT-derived sigma sections to (unspecified) strong disturbances in EMI data. I am convinced there is more than this to the difference in electrical conductivity imaging between the two methods. Primarily, I would say, it is a matter of the physical process that excites electrical current in either case: EM induction in one case, galvanic current injection in the second case. I would encourage the authors to use a word of caution in this respect in the revised paper, highlighting the intricacies underlying these physical processes.

I agree with this comment. Although there is a stronger spatial correlation between the 'conditioned' inverted EMI conductivity model with the ERI conductivity models, there certainly should be acknowledgement that the two have some differences due to the underlying physics of each method. The EMI is sensitive to subsurface conductive features, whereas the ERI is sensitive to resistive features.

(4) Information about homogeneity of soil saturation (lines 152-153: "The soil below 2.5 m depth is likely anaerobic due to periods of persistent saturation. While the water levels were not directly measured during the surveys, a chroma value ≤ 2 likely represents the seasonal-high water table at the site. ") and pore water salinity?

The porewater salinity (or conductivity) was not measured directly. However, ground water electrical conductivity of an agricultural field, roughly 300 m southeast of the current study site, was ~10 mS/m. This is likely representative of the current study site for the groundwater electrical conductivity for the assumed fully saturated sections of the ERI profile.

(4) The comparison between ERT lines and samples is only partial, as drillings only go down to 3 meters!

This was the limitation of our Geoprobe tool. The region of interest is primarily between the land surface to 3 m depth. This is where the expected subsurface transport is to occur due to water tables that can seasonally reach up to 0.5 m below land surface. We can cut the ERI image to a depth of ~ 3 meters to highlight the primary region of interest that also coincides with the maximum coring depths.

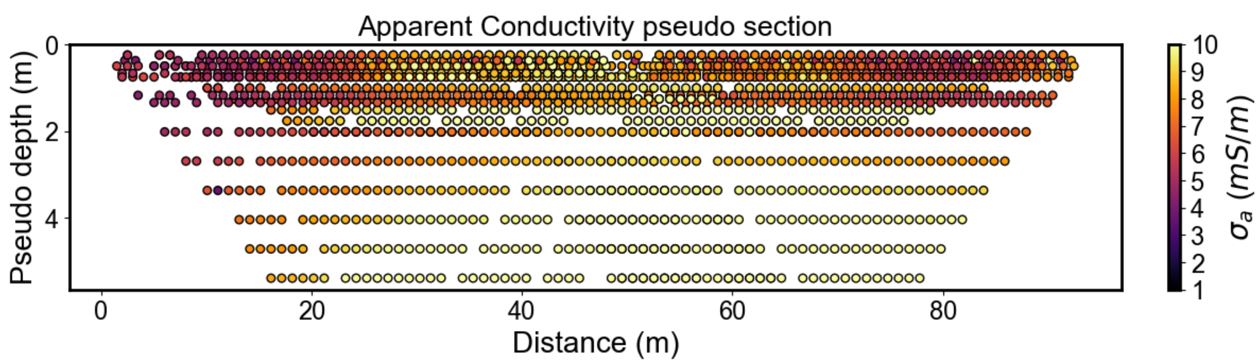
(5) Given the very small range of electrical conductivity in these 3 meters, the calibration towards soil properties is of course very weak.

Thank you for this comment. I agree that the uncertainty will be greater with a limited range of electrical conductivity values. It seems that the EMI does in fact have a relationship with the soil properties; however, the noise in the EMI measurements is masking this relationship. The ERI conditioning of the EMI measurements produces an inverted conductivity model that increases the spatial correlation between the EMI and the soil properties of interest. This is evidenced by Figure 8. Figure 8a shows the inverted conductivity models conditioned on the ERI and the d10 across all soil samples has a Spearman correlation of -0.608 whereas Figure 8e shows a Spearman correlation of -0.297 between the inverted conductivity models from EMI measurements not conditioned on the ERI and the d10 values across all the samples.

We would not have expected much more improvement because the inherent uncertainty of the controls on the soil electrical conductivity as measured by the EMI or the ERI. Clarity is needed with the revised paper to state that the measured conductivity is controlled by a number of subsurface features.

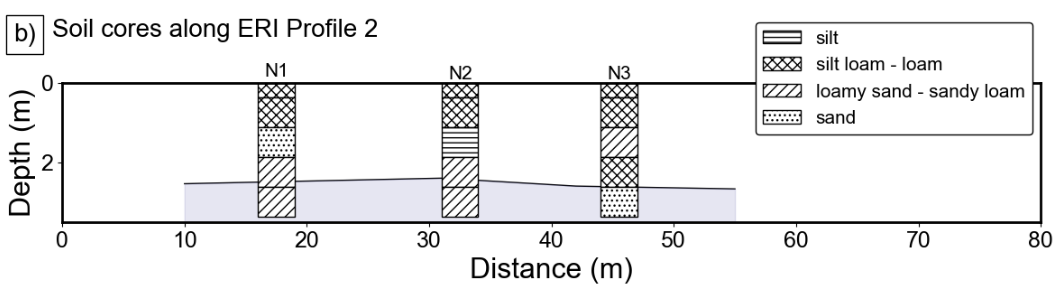
(6) I would have used much higher resolution for ERT, with shorter ERT lines together with the longer lines, in order to focus on the 3 m depth (mostly unsaturated, as far as it can be deducted from the indirect information reported above).

Both ERI surveys were roll along surveys. Thank you for bring the importance of this feature of the survey to my attention. The survey was collected of half of the electrodes for each survey and then moved one time. We also optimized the data collection within the top 3 m by using a short offset dipole dipole within out array sequence. The apparent conductivity profiles exemplify the regions of greatest data density is within the top 2.5 – 3m.



(7) Fig.2b: the different colors of the soil should have some meaning!

I agree that the colors should have some meaning or else I should remove the color altogether. I have the hatch marks and the color representing the same feature of the core. Below is the same profile just black and white.



(8) In subsection 3.1 The calibration-inversion-comparison (CIC) framework the references to Figures are probably all relevant to Figure 1 (not to Figure 3), albeit a general confusion exists (Fig.1d – or Fig3.d – does not exist!).

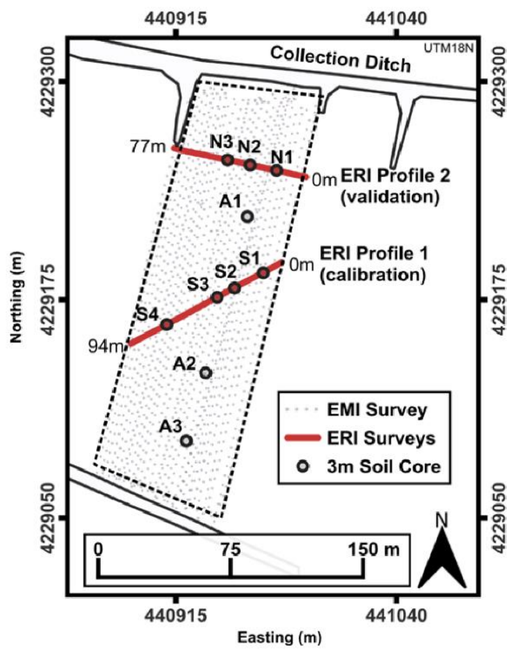
Thank you. In subsection 3.1, Figure 1 should have been referenced instead of Figure 3. Additionally, the Frame d was from a previous iteration of the manuscript. I will review the entire manuscript to ensure the reviewers can focus on the content and less on general manuscript errors. Also, I will have a colleauge who is not associated with this research to review the manuscript as an independent langauage review

(9) L.116-117: "the study field contains localized regions of elevation change (<0.5 m) that likely influence runoff generation." This type of microtopography cannot induce runoff, but rather ponding and thus local heterogenous infiltration processes.

Yes, I agree. Additionally, I have grain size data the shows there are finer grained soils within this region and supports the hypothesis of frequent ponding in this region of the field. I will update the description of the effects of microtopography on the infiltration processes.

(10) Fig.3: the dots indicating EMI measurements are indicated in red in the legend, but are gray in the image.

Agreed. The legend symbols do not match with the symbols for the EMI measurements. Figure 3 has been updated.

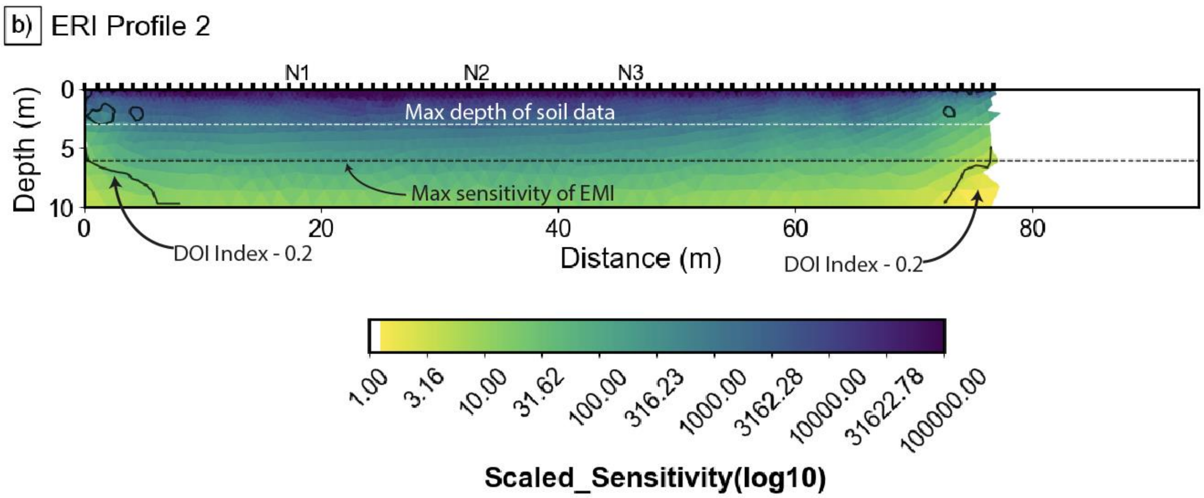


(11) L. 173-175: “A depth of investigation (DOI) index was computed (Oldenburg & Li, 1999) to define regions of the ERI conductivity model to exclude from the analysis.” The DOI is notoriously an overconservative approach based on a-posteriori sensitivity function: should we adopt it in all ERT investigations, the reliable depth would be of just a couple of electrode separations. In fact an ERT line can provide reliable information down to a much larger depth, namely 1/5 to 1/4 of the ERT line total length. At any rate at this point the authors should specify the average depth at which ERT data have been considered reliable. In comparison with the ERT images of Figure 5, I presume the DOI line (should be shown, it is easily produced by ResIpy – and so it says in the text, i.e. that the DOI line is shown, but I cannot see it in the figure) only goes down a couple of meters.

Based on this comment (11) in conjunction with comment (4) and (6), I will state that the greatest sensitivity is based on the DOI index (Oldenburg and Li 1999) and the sensitivity matrix (for review, DC RESISTIVITY AND INDUCED POLARIZATION METHODS Binley and Kemna, 2005).

The image below is for the reviewers but could be added to illustrate that the ERI has high sensitivity conservatively to ~6 m. The expected DOI of the EMI instrument is ~6.3

m.

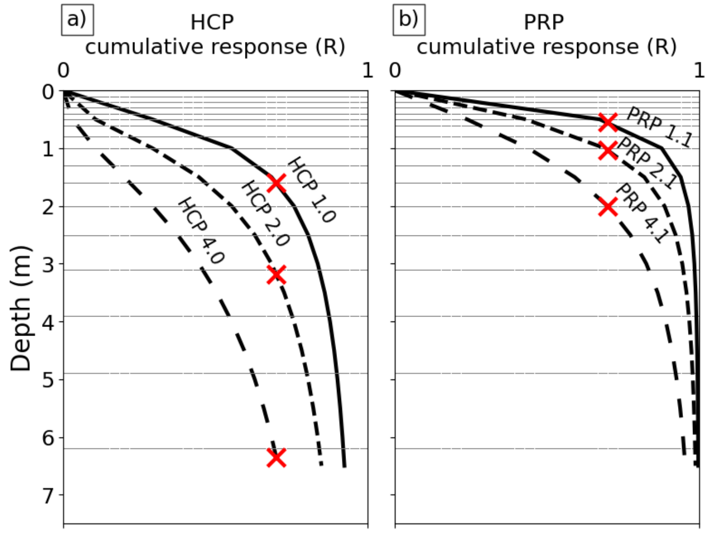


(12) Note that the electrode spacing is 1 m for both ERT lines: this implies that the maximum attainable resolution is 1 m, and as soon as depth increases such resolution declines sharply. Therefore it is really hard to try correlating the ERT pixel values with the evidence from geoprobe cores. The authors shall spend at least a word of caution in this direction: again, it would have been much better to use shorter, high resolution ERT lines (e.g. with 0.2 m electrode spacing) in roll-along configuration.

Thank you for this comment. I see that this research would have benefited from a smaller electrode separation. This does limit the relationship between ERI pixel values and the grain size data. However, the ERI-conditioned EMI measurements produce inverted conductivity structures are highly correlated with grainsize parameters (i.e., d10) that exceeds what the two methods can achieve independently.

(13) EMI inversion goes to 6.3 m instead, beyond the used ERT data, I presume.

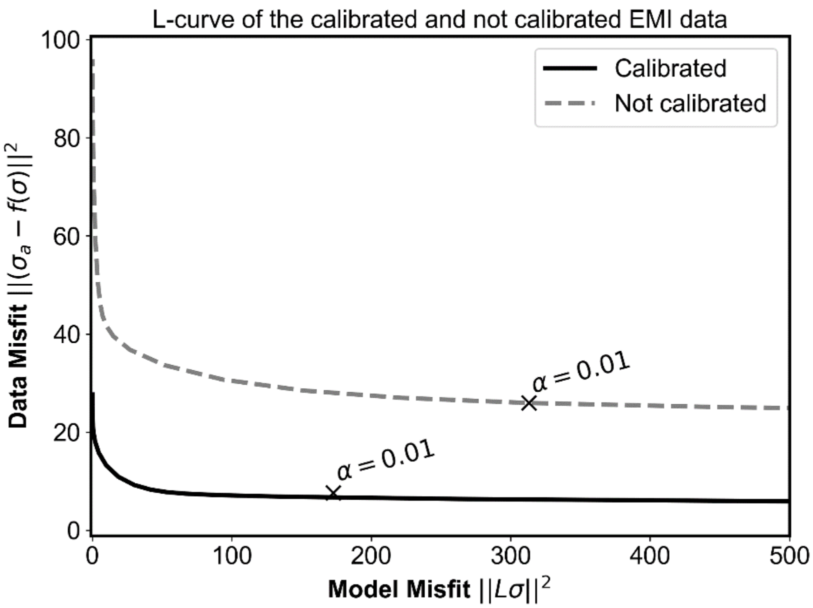
From the Figure presented in comment (11), the ERI sensitivity for the calibration can be used up to the 6.3 m depth based on the sensitivity of the EMI instrument. The figure below shows 3 black curves for (a) and (b), each respresenting the cumulative response of the coil geometry (orientation and separation). The red x’s represent the depth to which 70% of the instrument signal is attenuated and defines the maximum depth of exploration for that specific coil geometry. The light grey horizontal lines represent the depth binning of the inverted ERI conductivity model. The maximum depth bin is 6.2 m.

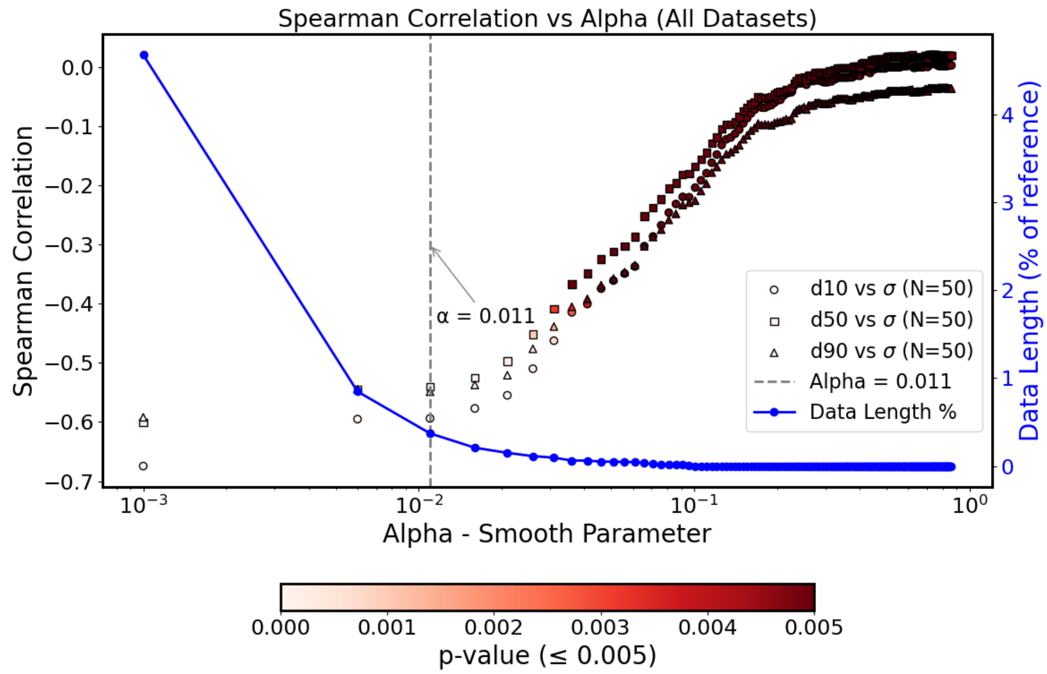


(14) L 221-223: "However, a lower α value, away from the elbow of the l-curve, was necessary in this study to ensure minimal smoothing of the calibration effects, which masked the relationship with the vertical soil profiles (discussed later). " I feel this is forcing the inversion to providing an apparent resolution that is not attainable with the Dualem 421S (that, from the name, has coil separations of 1 m, 2 m and 4 m)!

The EMI instruments have a cumulative sensitivity to the bulk electrical conductivity of a soil volume. The figure in comment (13) illustrates the Dualem 421S has the highest sensitivity within the upper 3 meters (i.e., more x's representing the assumed max sensitivity depth for each coil separation). The 1D inversion routines are needed to produce the most-likely conductivity structure that would give similar measurements as obtained from the field. In order to further justify the choice of the alpha value, a parameter-based sensitivity analysis was performed that iterated over alpha values from 0.001 to 1.0 in intervals of 0.005 and the ERI-conditioned EMI data were inverted. A Spearman rank correlation coefficient (left axis) was computed between the inverted conductivity model and d10, d50, and d90 from all soil core depths and locations. Also plotted is a representation of the non-physical values produced as a function of the smoothing parameter (alpha). By calculating the data length after removing non-physical values from the final inverted model and dividing by the total input measurements (% of reference) used for the inversion.

This figure illustrates the stark decrease of the correlation magnitude when comparing inversion conductivity outputs with higher alpha values. The choice of the alpha parameter was constrained by using a priori data in addition to comparing the L-curves between the conditioned and not conditioned EMI conductivity models. By comparing the two, we can ensure that the same value of alpha is shifted left (suggesting a low data misfit). There should be a check to ensure that the conditioned alpha value has a lower model misfit value for alpha=0.01 compared to not conditioned EMI-based L-curve.





(15) L.245-247: "To remove the effects of variably saturated soils, measurements were obtained under fully saturated conditions using synthetic groundwater with a constant, low fluid conductivity (0.1 mS/m) to evaluate the soil texture controls on the core-scale electrical conductivity." This is a bit puzzling, as in situ measurements are indeed run under variably (and unknown!) moisture content conditions.

Thank you for this comment. The goal for the lab-based measurements was to evaluate the influence of soil texture with a known moisture content. The lab-based conductivity models suggest that there are variations of electrical conductivity along each of the profiles that reflect the ERI conductivity variations across each profile. The lab-based measurements were intended to support the field work and not to provide a secondary caonditioning for the EMI. I will update the language in Line 245 to clarify the role of the lab-based conductivity measurements.

(16) L. 252: "Therefore, the core-scale measurements were conducted on the last 0.13 of the 3 m depth soil cores to capture conductivity likely from texture variation, given the known saturation and low fluid conductivity." It is unclear to me how this "known saturation" has been assessed as the water table has not been monitored on the site. Also, it is unclear why the authors only measured electrical conductivity of soil samples from the bottom (3 m below ground) samples. Indeed a more complete

characterization of the cores, also in terms of electrical conductivity (both saturated and unsaturated, with a complete characterization of the pressure-saturation curve as well) would have been highly beneficial.

I agree with the reviewer that a full electrical characterization would have been beneficial to this study. Because the water table was not measured at the time of the field surveys, we felt it was important to target the bottom portion of the soil cores to constrain the interpretation of the ERI conductivity models at depth, where changes in saturation is likely a control. The lab-based measurements illustrate that under constant saturation, there exist variations of electrical conductivity that are correlated with pixel values from the ERI profiles. Therefore, the ERI conductivity models are still showing changes in electrical conductivity that can be associated with changes in soil texture, even beneath the water table where conductivity values are higher relative to the top 2.5 m of the ERI profiles.

(17) Figure 5: it is visually apparent how there is a strong difference in electrical conductivity values measured on geoprobe samples taken along lines ERT1 and ERT2: yet the values in the corresponding locations in the two ERT lines are practically the same. This alone casts some doubts on any type of correlation attempt. I think the authors need to seriously address this evidence and convince the reader. This is particularly serious as these two datasets (ERT-measured conductivities and lab-based conductivities) are used as “ground-truth” to correct the EMI data, and yet they disagree with each other (in particular, the calibration versus the validation dataset).

Yes, I agree that a similar soil profile is not consistently represented across the two ERI lines. It is likely that the ERI survey locations has contrasting hydrology, and by extension different moisture content profiles along the soil column. The northern-most ERI profile is bounded by open ditches that are oriented perpendicular to ERI survey line. A deeper ditch lies parallel to the north ERI survey line. These open ditches are known to lower water tables and change the hydraulic gradients, especially within a few meters of the ditches. It seems reasonable that the northern-most ERI inversion produces a conductivity model with a lower range of values. The discrepancy between the two profiles is likely due to moisture content.

(18) The plots in Figures 6 and 7 must obviously show different variables, but while Figure 6 has the axis properly tagged, so is not for Figure 7… and the doubt remains that the scatter plots for uncalibrated sigma_a should plot in the same way in Figures 6 and Figure 7, but this is not so. Please clarify, and make the process clearer to the reader.

Thank you for this comment. Figure 6 and Figure 7 did not follow the variable from Table 1. Titles and variable naming consistency throughout the manuscript would improve these plots. Below are the changes I will make to address this comment:

Figure 6 title – "For Calibration: Offset of EMI data from ERI-informed simulated EMI measurements."

Figure 6 is σ_a [nc] (x-axis) vs $\sigma_{a, sim}$[cal] (y-axis). The graph represents the plot of the offset from the 1:1 line of field-measured EMI from a set of simulated EMI measurements that were constrained by the ERI conductivity model. The regression line is used for the conditioning whereby the EMI are adjusted to the 1:1 line.

Figure 7 title – "Post-Inversion: Comparison of EMI data and conductivity models produced from 1D inversions."

Figure 7 is a cross plot of the $\sigma_{a, inv}$[c] and $\sigma_{a, inv}$[nc] (both on the x-axis) and $\sigma_{a,}$ [nc]. This plot uses the last simulated conductivity model from each 1D inversion. We use this to simulate measurements that would likely produce this specific conductivity structure. The similairty of the simulated EMI measurements from the inverted conductivity model and the field-measured EMI provides confidence that the final conductivity models are highly likely to represent the 'true' subsurface conductivity patterns.

(19) L 319: "A striking result of the effect of the EMI calibration is highlighted in Fig. 8a-8d, with marked increases in correlations between all d finer classes and σ EMI [c]." I would be much more cautious in this respect. The correlation remains really poor no matter if the sigma values come from corrected o non corrected EMI inversions. This is obvious, as a visual inspection of the core descriptions in Figure 4 do not find any

correlation in the ERT lines in Figure 5 (that are anyway considered as “true” values of conductivity).

It is likely that the description of the ERI needs revision. I think that the relationship between the EMI and change in soil properties lies within the EMI data itself. Indeed, the ERI profiles do not show a consistent relationship with the soil horizons. The ERI calibration equations seem to act more like a spatial running mean of the data. Therefore, we can avoid assuming that the ERI is considered the true model. This strengthens the argument for more EMI surveys to be calibrated with ERI measurements and lends the calibration equations to a similar range and spatial distribution of electrical conductivity values.

Despite the differences between the ERI and the soil profiles, it is still useful to compare the EMI and ERI to show that the inversion produced a similar EMI image as the ERI. Again, any similarities to an ERI image that was not used in the calibration, is interpreted as ‘revealing’ a relationship that already exists between the EMI and ERI.

(20) I find the comparison in Figure 9 problematic: it is true that the correction seems to indicate a better correlation between lab samples and field EMI results: but the values of either dataset are totally off!

Yes, I agree that the EMI conductivity models are not along the 1:1 line when comparing with the lab samples. The discrepancy is expected because the soil cores and EMI measurements were not collected within a single field campaign. Therefore, any relationship may suggest, at least at the soil sampling sites, an unchanging lateral (x,y) conductivity structure at a depth of 3 m where saturation changes seem to modify the magnitude.