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 1

Red Text – Author Response

This manuscript is interesting and built upon existing literature on the use of calibration for EMI. The Authors described the process in detail with great pedagogy and highlighted the advantage of calibrated EMI to relate it to soil texture for agricultural application. I believe it will make an interesting manuscript to be published in SOIL, certainly with the greater use of these sensors with the rise of agrogeophysics. Please find below some major and minor comments to be addressed.

The title of the paper focuses on soil texture and EMI but, if I understand well the driver below, it's an agricultural problem that is the reason this study was carried out. I would try to highlight more the agricultural context in the introduction (as you already come back to it in the conclusion). I think highlighting the value of your study in this context can increase its impact. I also propose a rephrased title that highlights this context (see below).

Yes, I do think that emphasizing the agricultural context would improve the current manuscript.

In the revised manuscript, I will go into more detail into the nutrient loss characterization (L32). The nutrient loss potential relies on soil drainage classifications and hydrologic groups both retrieved from SSURGO for the dominant soil group within the field. However, the subsurface nutrient transport usually occurs through coarse-textured soil (with high permeability) in an otherwise dominantly fine-textured, poorly drained soil. This emphasizes the site-specific resolution needed to provide best management practices for farmers and land managers.

I would more clearly make the distinction between apparent and inverted EC values throughout the manuscript. In literature, often ECa is directly compared to soil texture but here only inverted EC is used for comparison. I would add information about the distinction apparent/inverted and discuss the choice of the use of inverted ECa for comparison.

I will address this comment in a later comment. I do agree that a greater distinction is needed between apparent and inverted EC and the increased confidence when comparing inverted EC with depth-specific soil property data/model.

In general, the manuscripts read well but, in some places, missword endangered the meaning of the sentence. Please carefully re-read the manuscript to ensure its meaning is as you intended.

Thank you for this comment. Your comments provide concrete examples of where this has occurred in the manuscript. I will re-read the manuscript and spot other sections in the manuscript that could use clarity. Also, I will have a colleague who is not involved in this study to read the revised manuscript for an independent language review.

Detailed comments:

title: the agricultural nutrient loss aspect does not appear in the title while it's still a main driver of the manuscript. In addition, a lot of literature already exists on EMI to map soil texture, so it does not feel very new (even though the relationship still remains challenging I acknowledge). Maybe rephrase as: "How resistivity calibrating EMI surveys, improve soil texture prediction and nutrient losses from agricultural fields" or "Agricultural nutrient losses: improvement from resistivity calibrated large-scale EMI surveys" or smth similar.

I will consider this. I do think a name change could speak more to the output of this work, which is improving nutrient loss assessments. One coauthor suggested to go with a title similar to your second suggestion:
"Agricultural nutrient losses: improvement from resistivity calibrated large-scale EMI surveys"

L23: 'is significantly improves' -> improving?

Agreed.

L32: 'surface drainage tiles' -> also subsurface drainage tiles no?

There are no subsurface drainage tiles in this field. The subsurface drainage tiles are not used often. The conventional approach is to have shallow (~2m) open ditch bounding the field. These are all connected to a larger 'tax' ditch which is usually deeper (~5m).

L46: What about temperature? (2% increase of EC with each degC)

Agreed. Yes, temperature is an important control on the measured electrical conductivity. I will include this into L46

L56: 'electrical resistivity geophysical method' -> 'ERI'?

Agreed. We have already defined the ERI method. It is better to stay consistent with the terms.

L56: 'approximate' -> I am not sure about the term here. It actually measures a property linked to sigma, then uses an approximation (LIN) to get an apparent sigma.

I will change from approximate. I think this is one example of the needed clarity from your general remarks.

L57: 'the electromagnetic inductions methods ...' -> here I would have expected a short explanation of the EMI method (induction of eddy currents proportional to soil sigma, measuring primary and secondary electromagnetic field,...), to put it into perspective with ERI as it's the first part of the sentence. Only then I would go into the difficulty of the environmental influences. Note that ERI too can suffer from 'environmental influence' (e.g. cable coupling) but much less than EMI ofc.

Yes, providing a brief description of the EMI method, along with the appropriate references, will contextualize the explanation of the measurements noise.

I would specify somewhere here that we are dealing only with frequency domain EMI and not time-domain (TEM).

I will update Line 44:

"Frequency-domain electromagnetic induction (herein after EMI) and electrical resistivity imaging (ERI) are increasingly applied..."

L70: "the impact of noise" -> from my experience, calibrating EMI with ERI transect will bring two things: (1) it will ensure that the sigma_a from EMI is linked to the soil sigma and (2) it will ensure all different coils configuration have the same relationship to soil sigma. What we often find in commercially available instruments is that each coil is calibrated individually by the manufacturer over a homogeneous ground. But these independent calibrations can drift in time and do not guarantee that the data from all coils together is consistent. When inverting uncalibrated data, you can often see one coil configuration worse fitted than others. Calibrating all coils to the same object (ERI) ensures they can all be fitted together within an EMI inversion routine.

Thank you for this comment. I agree to comment (1) that the calibration provides a link between the EMI measurements and the soil sigma. Comment (2) makes so much practical sense. We usually see the HCP1.0 of from the Dualem-421S has a consistently worse fits (seen in Figure 7a) relative to all the other coil configurations. I will look deeper into the Dualem's calibration.

I would also emphasize here the difference between an apparent value and an inverted value. Often in study, apparent values are compared to depth-specific textural property but that's not what is done in this study (and I am happy with that). More explanation on why EMI data are inverted to make the link with soil texture is needed.

Addressed in a different comment, Page 8 of this document.

I think a difference must be made here if the calibration improves the EMI inversion or if the calibration improves the sigma_a approximation. Von Hebel et al. (2019) and Hanssens et al. (2019) both propose an 'equivalent EC' or 'robust ECa' method to obtain a more robust sigma_a without the limitation of the low induction number (LIN) approximation.

Yes, I agree. The improvement of the EMI inversion comes from the calibration of sigma_a. Per your comments, it seems that the calibration 'binds' measurements from each coil configuration to a single reference. Thus, this produces mode improved inversion results.

L112: add truncated gps wgs84 coordinates

I will include this for the primary study field.

fig2: add CRS used for the northing/easting (utm?)

I will include WGS 84 / UTM 18N for the CRS of the northing/easting.

L112: "water tables" -> "water table"

Agreed.

fig2: you mention the elevation in the field to change slightly. If you have an elevation map of the field. I would add it here, in addition to subplot b. I would then remove subplot a and just put the us map as inlet on top right of subplot b.

I have LIDAR from the site. I will include the LIDAR-based elevation map. Removing Figure 2a will make room for the elevation map to be included.

L134: the instrument was "walked in" so it was carried? at which distance from the ground? Was this distance negligible or included in the inversion?

I will make it clearer in the manuscript. The EMI instrument was pulled behind one person and was directly on the ground and the height above land surface was considered to be negligible.

L136: 1 m spacing ERI will lead to a relatively coarse resolution close to the surface where most of the EMI sensitivity is located. This will also have limited the resolution of the ERI to delineate the soil layers. However, it is able to cross the entire field and as such span a large difference in sigma_a from EMI. Von Hebel et al. (2019) uses 0.25 or 0.5 m electrode spacing. Maybe smth to add to the discussion.

Yes, the ERI could not delineate soil layers well. I really appreciate the suggestion about crossing such a large span of the field. Reviewer 2 suggested a roll along

It might be interesting to have the original soil map (without EMI interpretation) for comparison or just juxtapose the boundaries of it.

I think this would add to the outcomes of this research. The EMI clearly resolves texture and shows conductivity variation that is related to surface features (surface scarring) that are known to promote surface ponding in the field. I will use a similar figure as shown below to highlight the soil maps obtained from SSURGO.

There are defined hydrological drainage classifications for each soil unit.

mwd-moderately well drained

wd – well drained

pd – poorly drained

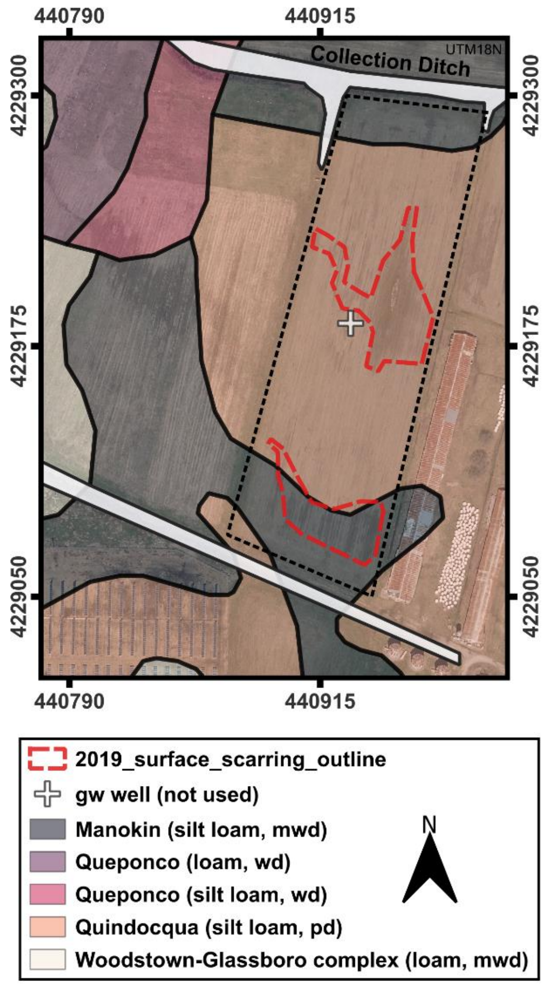

fig4: I would add the water table at the time of the survey in addition to the grey zone.

I'm looking into obtaining data from two observation wells that flank the field. I will include any relevant water table information obtained from this data.

L158: "pre-calibration" -> I would not call it like that, it's not a calibration. The resistance value measured does not need to be calibrated. Just put "Electrical Resistivity Imaging (ERI)"

Yes, I agree. This suggests the ERI data also needs calibration. I think removing 'Pre-calibration" will make the subsection concise.

L165: "between 1200-1500" -> it wasn't constant? or is that because you filter some data out?

There was a different amount of data filtered from each ERI survey. I will make sure this is clear in the revision of the manuscript.

L165: "with ~43% containing" -> rephrase like "for each sequence 43% of measurements were added as reciprocal"

Agreed. I will rephrase to provide clarity.

L166: 'current and electrodes' -> 'current and voltage electrodes'

Agreed. Thank you.

L169: 'ResIpy' -> 'ResIPy', please add version used when mentioning code

Agreed.

L176: these eddy currents are more or less strong depending on the soil conductivity (that's the link to soil sigma!)

Thank you for this comment. I led the reader to this point but never made the most important connection here on L176.

L195: "average distance" -> you mean all EMI points within 1.5 m from the ERT profile were average for this profile or you mean that you took the 10 closest points and their average distance to the ERI point was 1.5 m?

I took the 10 closest points and their average distance to the ERI point was 1.5 m in the (x, y).

L197: where do the 816 simulated models come from? Is that because you have a model every 0.5 m along the ERI line?

Yes, the 0.5 m binning along the ERI profiles influences the amount of co-located EMI data. I had 136 EMI measurements that were considered co-located with conductivity along the ERI survey.

L203: "8 mS/" -> "8 mS/m"

Agreed. Thank you.

L209: "forward model (m)" -> "forward modeled data (m)", the 'forward model' is the operator. Usually m is the vector of model parameters (so sigma values here). f(m) is the forward modeled data = simulated data based on m. So if should be ...d_i - f_i(m) is the i-indice to refer to the coil configuration (and you have one forward model for each coil configuration as they have different sensitivity functions).

Yes, I agree with the reviewer. I will make the modifications to the equations to make the distinction between the forward model data (m) and the forward operator (f). I will include the variable index on each to reflect the coil configuration.

L252: "below 2.5 m" -> why is that? isn't it just because of lower sensitivity of the EMI? also aren't completely saturated at 2.5 m depth, so soil moisture variation shouldn't matter => or you mean "above 2.5 m depth" that would make more sense actually

I do mean below 2.5 m. A groundwater level was not measured during the surveys. Therefore, it is less certain to assume that >2.5 - 3m is below the water table. We currently rely on soil color changes to infer an 'average water table depth'. However, we are seeking data regarding the water levels at the site.

fig5: we salute the use of a uniformly perceived color-scale instead of the usual rainbow/jet. Thank you!

Thanks!

fig7: maybe it would also be nice to have a visual comparison of the transect: inverted ERI, uncalibrated inverted EMI on the same transect, vs calibrated EMI on the same transect.

I will include this visualization either in the manuscript or in the supplemental data. I do agree that this will be an easy way to compare the EMI and ERI results.

fig8: why don't we have a 0.38 m sample for the nc case? it seems they matters to improve the relationship when you look at the calibrated plots.

Yes. The lack of 0.38 m samples for the not calibrated EMI conductivity model is due to the number of non-physical values produced by the inversion at a smoothing value (alpha) of 0.01 for the EMI inversion. Since both calibrated and not calibrated inversions were inverted using the same alpha value, this shows the calibrated EMI measurements produce less non-physical conductivity values (i.e., negative conductivity values) at the same alpha value. Additionally, any increase in the alpha value seems to smooth out any relationship within the top 0.75 m. I can present in the supplemental a graph from a sensitivity analysis of the not calibrated inversion routine and iterate of alpha values. Each iteration, I will compute the Spearman correlation between the grainsize parameters and the not calibrated EMI conductivity models.

fig10: I would add the inverted nc and c transect here too for a visual comparison (even if an visual improvement will be difficult to see)

Thank you for this comment. I will include the transects for the EMI and ERI.

L365: "...reduced RMSE" -> this shows well that the calibration helps the inversion by "binding" all coil to the same calibration (as I commented above)

The ‘binding’ all coils to the same calibration is such a clear way of describing the effects from the calibration process on the EMI measurements. I will make sure to include this within the discussion near L365.

L383: yes, this should be emphasized from the start I think

Yes, I should clarify that the ERI-based calibration of EMI measurements provides a significantly stronger and more physically meaningful relationship with lateral and vertical variations in soil texture. I should include this in the introduction and highlight the vertical variations can inform nutrient leaching potential, while the horizontal changes can help delineate regions of textural change that may promote rapid subsurface groundwater (and by extension nutrient) transport during rainfall events.

fig11: while it's interesting to see if your calibration equations applied outside of your field and that they improve the inversion; the dataset you have is not the best as you don't have any validation data from these other fields (no ERT or cores). So it's not a really quantitative comparison. I would highlight this limitation.

Agreed. This is purely a qualitative comparison. The initial results may be promising; however, the ERI-based calibrations should not be thought of as the only way to improve the relationship between EMI conductivity models and the relevant soil properties. The silt-loam fields of the Delmarva used in this study find benefit in the inversions from the calibration. However, there is likely a suite of situations where the calibration is less effective and may require alternative calibrations/conditioning methods.

discussion: I would add to the discussion the effect of soil moisture. You mention that in saturated conditions, EC is driven by texture but often you have an unsaturated zone at the surface, where the EMI sensitivity is the highest. What could be the effect of this unsaturated zone on your results and how the calibration interacts with it (as we see it's mainly the shallow coils that have strong calibration equations).

I will include a greater discussion on this comment. One uncertainty is the time scales the moisture content will change. Collecting EMI measurements shortly after rainfall may mask the soil texture relationship. For example, saturated sandy soil could likely have a conductivity magnitude roughly equivalent to a partially saturated clayey region of the field. Thus, careful interpretation.

The approach you propose relies on inversion of EMI data and this inversion carries with it its uncertainty. Numerous papers do not invert ECa and directly correlate it with depth-specific soil texture. Why did you choose to invert the data? What could be the uncertainty inherent to the EMI inversion introduced by this process?

The ECa as measurements from EMI instruments measure a depth-averaged conductivity along the sensitivity range for each coil configuration. Many of the comparisons with soil properties and ECa are considering soil property changes across the landscape of interest and do not consider the conductivity changes in the vertical direction. Relevant to this study, the information along the vertical direction can provide information regarding the variation in nutrient leaching potential across the site. It is also known that in the low-relief agricultural fields, subsurface transport of Phosphorus is known to occur. The ability to characterize soil horizons (or generally multi-depth soil properties) is essential in agricultural studies. I would expand on these topics to reinforce the nutrient transport component of this study and further emphasize the need for inversions when comparing depth-specific data/models with the EMI inverted conductivity models.

ref: there are two McLachlan et al. (2021), one for boxford and one for emagpy, if emagpy is used for the inversion, please mention the software version.

Agreed. This was a large oversite on the Author's part. The EMI inversions and calibration were performed in EmagPy and was essential for the overall analysis from this study. I will include the EmagPy version number as well.

I encourage the Authors to make their code available on an open platform (github, gitlab, zenodo, ...) and cite it in their work. That will ensure their CIC process is reproducible by others.

I will provide Jupyter Notebooks and data for all analysis performed. I'm currently preparing the notebooks for sharing.