RC1: General comments

This preprint presents an application of complex electrical conductivity to estimate soil organic carbon (SOC) at greater depths, with the objective of supporting more realistic soil carbon stock assessments. The topic is timely and relevant, and the work has the potential to contribute to a better understanding of deep soil carbon pools, which are still poorly quantified. I agree with the authors that geophysical methods offer a valuable opportunity to collect quasi-continuous information about subsurface properties in a non-invasive manner, which represents a major advantage over conventional sampling approaches.

However, I would like to preface my review by noting that my expertise lies in the direct analysis of SOC in surface soils, and not in geophysical methods. Therefore, I am not able to fully evaluate the technical aspects and methodological robustness of the CC approach. My comments mainly concern the clarity and effectiveness of the scientific communication.

In its current form, the manuscript follows the structural requirements of BG Letters, but in my opinion the overall message would benefit from improved contextualization and clearer explanation of the methodological basis supporting the conclusions. In particular, the introduction does not clearly convey why quantifying SOC at depth is critically important for carbon budget assessments. Since this aspect appears to be central to the significance of the study, a more explicit rationale would strengthen the manuscript.

Moreover, while the authors state that their results demonstrate the ability of the CC method to map SOC pools at varying depths, the discussion does not convincingly communicate the robustness of the evidence supporting this claim, especially for readers unfamiliar with the technique.

Dear Reviewer, thank you for your comments. It helps us to put our manuscript in perspective and improve the message for a wider community.

To address the comments from the reviewer, we consider large edits in the “Introduction”. We will include a larger revision of the recent results observed in laboratory from measurements in organic soil samples, as well as a previous study working on a shallow peatland. The text should make it clear that the objective of the paper is to demonstrate the possibility to use complex conductivity to non-invasively identify variations in SOC at varying depth and in an imaging framework.

We believe that such edits in the “Introduction” should make it clear the necessity of investigations as those presented in our study, where the method is tested in deeper investigations and in mineral soils, related to low SOC. We will also relate to recent studies addressing the necessity to investigate deep carbon stocks, for instance in arctic soils.

Specific comments

1. Importance of deep SOC

The introduction presents the commonly known limitations of estimating SOC in topsoil, but it remains unclear why mapping SOC in deep soils (>100 cm) is particularly relevant. The authors should explicitly state the implications of deep SOC for long-term carbon storage, carbon budget accounting, or soil management strategies. Clarifying this would help readers appreciate the relevance of the study.

The importance of deep carbon pools has been addressed in a few studies cited in the initial manuscript submitted. In the revised version of the manuscript, we extend the list of references, and in particular we point to carbon pools in thawing arctic soils.

2. Description of the method and presentation of results

Although the methods are described in the appendix, as required by the BG Letters format, the manuscript would greatly benefit from a brief explanation in the main text summarizing how the experimental design allows testing whether the CC method is suitable for estimating SOC at depth. Providing a brief explanatory sentence or two in the main text about the rationale of the approach and how the measurements link to SOC estimates would significantly aid comprehension. This is especially important for a Letter format, where the main message must be quickly accessible.

The manuscript has been edited. In particular, we have severely edited our "Introduction" to include a brief explanation of the method and a improved revision of the literature that stress the link between SOC and electrical properties as observed from laboratory measurements in recent publications.

The manuscript would also benefit from explicit references to the appendix where methodological details are provided. This would guide readers who wish to understand the technical basis of the results.

We appreciate the suggestion of the Reviewer. We extended the details explaining the physical principle and application of the method in the Appendix. We also added further references there.

Considering the limited methodological explanation in the main text, the robustness of the results is not clearly communicated. The authors should better articulate how the presented data support the main conclusion that the CC method allows mapping SOC pools at depth. In addition, the manuscript would benefit from a more explicit discussion of potential limitations or constraints of the presented evidence, such as sources of uncertainty, methodological assumptions, or conditions under which the approach may be less reliable.

We have addressed the comments from the Reviewer and improved our formulations. In the discussion, we have now included a paragraph addressing the uncertainty in the interpretation of the geophysical results. This is a well-known problem in the geophysical community; thus, we initially decided to omit it. Nonetheless, we agree with the reviewer that such discussion is key to evaluating our results and the applicability of the method. We added a new Appendix, in which the accuracy and sensitivity of the method is tested by means of numerical simulations after varying the size and contrasts of a polarizable anomaly, related to varying the size and SOC of the carbon stock.

3. Figure 3

Figure 3 is difficult to interpret for readers not familiar with the technique. Since it seems essential for supporting the reliability of the conclusions, improving its readability (e.g., clearer legends, explanations, or visual simplification) would significantly enhance the manuscript.

We thank the comments from the Reviewer and we have improved the caption to Figure 3 and edited the labels and added some notations to facilitate the interpretation. We hope that the edits on the Figure

address the concerns of the Reviewer.

Technical corrections

Next list of suggestions have been implemented in our manuscript

Please write out all acronyms when first mentioned.

- Line 14: “we show that an increase the polarization effect” → grammatical error.
- Line 82: “with lower values ~20 mS/m)” → misplaced parenthesis.
- Line 137: “our sample sis beyond” → typo (“sample is”?).

RC2: Major Comments

1. Insufficient explanation of the mechanisms linking σ′ and σ″, and their relationships with SOC and σ″. The introduction section did not adequately explain the theoretical background of σ′ and σ″. Each parameter represents what and how the two are related in the context of SOC interpretation.

To address the comments from the reviewer, we consider large edits in the "Introduction". We introduce now the conductivity and capacitive properties of the soil expressed by means of σ' and σ'', followed by an improved revision of the literature linking those electrical parameters to SOC as observed from recent studies in the laboratory. These comments also address the concerns of the Reviewer 1.

2. The conclusion that the polarizable anomaly "can only be explained by variations in SOC (Lines 119–120)" is too strong, given the range of possible contributors to σ″ in mineral soils. The frequency dependence of σ″ is central to the interpretation, yet the manuscript did not sufficiently justify why SOC-driven polarization should peak at ≤1 Hz, particularly in light of previous studies reporting variable frequency responses. Please provide quantitative or experimental evidence that rules out alternative explanations. I would also recommend providing more comparisons between your observed frequency patterns and those reported in previous studies, along with a clearer justification for why the low-frequency peak is diagnostic in this case.

To address the comment of the Reviewer, we have edited the introduction, where now we provide a more detailed revision of the existing literature lining the complex conductivity with soil properties and, in particular, with organic carbon. These references are used in the discussion to sustain our interpretation.

3. Lack of quantitative uncertainty analysis for the inversion results and SOC estimates. Although the manuscript acknowledges the mismatch in sampling volumes, no quantitative uncertainty assessment is provided. Additional analysis of uncertainty or sensitivity is necessary, given that the interpretation relies on the subtle differences in σ″ between B1 and B2.

We agree with the reviewer, and we added a new Appendix where we discuss the sensitivity of the imaging results. We address the comments from the Reviewer through a numerical study in which the accuracy and sensitivity of the method is tested by means of numerical simulations after varying the size and contrasts of a polarizable anomaly, related to varying the size and SOC of the carbon stock.

4. A number of typos were found in the text, so the language and grammar should be further checked throughout the manuscript.

We appreciate the comment from the Reviewer. This has been corrected.

Minor Comments

The following lines have been corrected:

Line 56: is "66 ha catchment" correct?

Lines 94–96: The authors note that CEC values are similar in B1 and B2, but they do not discuss the

potential implications of this observation, particularly given that mineralogy plays a major role in SOC stabilization.

Line 134: Please confirm whether the correct spelling is “McAnalen” or “McAnallen”.

Line 137: “sample sis” seems to be a misspelling.

Line 147: “soil organic caron” should be “soil organic carbon.”

Line 229: Figure A2: The unit μS/m should be made consistent with the main text, where mS/m is used in the preceding sections.