Author comment for RC2

Dear Anonymous Referee #2,

Thank you very much for your time and effort in thoroughly reviewing our manuscript. The constructive comments and insightful suggestions have been invaluable in helping us improve the manuscript's scientific rigour, clarity of presentation, logical progression, and overall organisation. We have carefully considered each comment and made comprehensive revisions throughout the manuscript. Our detailed point-by-point responses are provided below.

Black- Reviewer comments

Green -Author comments

Underlined text - new text/ changed text to add to the manuscript

RC2:

The paper describes a data analysis technique based on Boundary Line Analysis to identify which soil properties limit SOC accumulation in the topsoil and to what extent. The authors draw conclusions about which values of soil properties are ideal for SOC accumulation. They then present a methodology, tested on a specific farm in Australia, for site-specific determination of SOC sequestration potential and limiting soil properties, which can support the application of targeted carbon farming practices.

Overall, the research is interesting and shows great practical potential to aid decision-making in carbon farming and help land managers identify which targeted practices to apply for the biggest gain in SOC content. The work is well-rooted in previous publications, and the methodology is explained in sufficient detail. The methods developed in this paper have the potential to be applicable internationally, however, some aspects need clarification to allow broader applicability. The paper is also weak in terms of structure and writing style. The writing requires significant revision before the paper meets publication standards. I would like to urge the authors to tighten the logical structure, the correctness of their sentences, and their grammar throughout the paper. Furthermore, the results section could be significantly shortened. Much of the analysis consists of panel-by-panel descriptions of figures, which adds limited value, as readers can extract this information directly from the figures themselves. The discussion should not describe the figures in detail, only point out relevant features and reflect on their significance. The figures are frequently described without being used to draw meaningful conclusions. In addition, some tables and figures could be excluded without sacrificing any relevant scientific findings, and most figures require improvement in terms of presentation.

Response: Thank you for your detailed and constructive comments. We appreciate your positive assessment of the scientific relevance and practical value of this study, particularly the proposed Boundary line analysis (BLA) framework. We are encouraged that you recognise the

potential of this approach to support site-specific carbon farming by identifying soil properties that limit SOC accumulation and helping to guide targeted management practices.

We acknowledge your concerns regarding the manuscript's structure, writing quality, and overall presentation. Accordingly, we will extensively revise the manuscript to improve its organisation, grammar, clarity, and scientific expression. We agree that the results section is overly lengthy, particularly the description of the subsoil findings. We will merge the presentation of the topsoil and subsoil BLA results (Lines 318–462) and substantially condense this section by focusing on the key findings and differences in topsoil and subsoil findings, rather than describing every detail of the results of BLA models. We will also shorten the description of the attainable SOC and limiting-factor maps (Lines 523–634), highlighting only the most important spatial patterns and dominant constraints.

The figures are described in the results section, and conclusions/inferences were drawn in the discussion section. In addition, all tables and figures were carefully reviewed. Tables 6 and 7 have been merged into one, as shown in the later comment.

We believe that these revisions have considerably improved the manuscript's clarity, coherence, scientific depth, and overall suitability for publication.

Comments concerning the content of the paper:

- It is stated that this method can be applied to the 72 farms involved in the study, provided that they have digital soil maps. However, broader applicability is not discussed. Can this BLA model be applied to other farms in Australia that were not used for the fitting itself? If not, what would be required? How readily could this be applied in other countries, and what is its international relevance?

Response: Thank you for raising this important issue. We agree that the international applicability and reproducibility of the BLA model should be discussed clearly. Yes, this BLA model can be applied to other farms, provided they have data to make a DSM so the BLA model can be updated; or, if no SOC data is available, much care would be needed to ensure we weren't extrapolating. In terms of international relevance, this Model could be applied anywhere - provided that a model that represents the region/area is created. That means, in other countries, many have their own databases, so they could use the same approach and make their own BLA. In addition, to support reproducibility and allow others to apply the method, we will publish the code for performing the BLA with a simplified and shareable dataset for reproducibility purposes. In the future, our intention is to create a RShinyApp (or something similar) where people can enter their data and location to get an attainable SOC estimate for their location.

Therefore, we have added relevant text to the Abstract and Discussion, as presented below.

Proposed text for abstract (next to L36): *"The BLA framework can be applied internationally where suitable regional or local soil and SOC datasets are available to recalibrate these BLs or develop new, locally representative models.*

Proposed text for discussion: ***"****The BLA relationships developed in this study could also be applied to Australian farms that were not included in the model development, provided that their rainfall patterns and soil-forming conditions are similar to those covered by the calibration dataset. Digital maps of the required soil properties would also be necessary. However, predictions beyond the environmental and soil-property ranges represented in this study may be less reliable and should be validated using independent observations. For farms with substantially different conditions, the BLA relationships would need to be recalibrated using additional representative data.*

The BLA framework could also be applied in other countries; however, the boundary relationships developed for Australian grain-growing soils may not be directly applicable to other soil and climatic conditions. International application would require representative local SOC and soil-property data, an appropriate climatic classification, local model calibration and validation, and suitable digital soil maps. Therefore, the main international relevance of this study is the transferable methodological framework rather than the direct use of the Australian boundary relationships."

- I suggest to discuss BLA further in the introduction, including its potential weaknesses. This point also arises in the discussion where BLA is compared to linear regression. It is only stated that BLA results in higher attainable SOC estimates (L650–655), which does not necessarily mean it is more accurate. The authors should justify why estimates from BLA should be more trusted than those from linear regression.

Response: Thank you for the suggestion. We agree that our original discussion did not sufficiently justify the use of BLA and that a higher estimate of attainable SOC does not necessarily indicate greater accuracy.

The manuscript already referred to previous studies comparing BLA with linear and quantile regression. However, we will revise this section because the previous wording could be interpreted as suggesting that BLA was preferable simply because it produced higher attainable SOC estimates. We will clarify that BLA and linear regression estimate different quantities. Linear regression estimates the mean SOC response across all observations, including soils that may remain below their attainable SOC because of other environmental or management limitations. In contrast, BLA estimates the upper envelope of the relationship and is therefore more closely aligned with the objective of estimating attainable SOC.

We will also clarify that this conceptual suitability does not demonstrate that BLA is inherently more accurate. The revised Introduction and Discussion will acknowledge that BLA estimates may be sensitive to the selection of boundary observations, outlier removal method, data density, the observed range of soil properties and unmeasured interacting factors.

- In section 2.5 it is unclear what is meant by a 3D data cube. What is the third dimension, is it depth, or soil parameters? I assume that it is depth, with separate RF models trained for different soil properties, but this is not clearly stated. It would also be valuable to include some reflection on how the accuracy of the digital soil map, discussed via the validation metrics in section 3.3, potentially impacts the results and the validity of the final limiting factor and attainable SOC outputs.

Response: Thank you very much for your comment. Yes, in the 3D data cube, the 3rd dimension is depth, which will be included in Section 2.5. We also recognise the impact of the accuracy of the DSM on the final limiting factor map and attainable SOC outputs. We will expand this in the discussion to explain how digital soil mapping accuracy affects the attainable SOC and limiting-factor outputs.

- The results section should be more concise, as it currently contains overly detailed descriptions of the figures without sufficient reflection. One suggestion that I believe would improve the conciseness is merging sections 3.1 and 3.2, as the observed trends are often very similar and the same statements are repeated with slightly different but largely irrelevant numbers. This would allow common relationships to be stated once, with differences discussed and reflected upon. Also, individual subplot values should not be described exhaustively, only interesting features, outliers, and their interpretation should be highlighted.
    - For instance, why is the shape the same for clay% and silt+clay%?
    - In addition, parts of the results section would be better placed in the discussion (for instance, L545–550).
    - Figure 10 is the main result and should receive the most attention, rather than being overshadowed by the lengthier discussion of earlier figures.

Response: Thank you very much for your insightful comments. Yes, we agree that the results section is overly lengthy. Based on your suggestions, we will merge sections 3.1 and 3.2, shorten the description of the results, by focusing on the key findings and differences between topsoil and subsoil, rather than describing every detail of the BLA model results. We will also shorten the description of the attainable SOC and limiting-factor maps (Lines 523–634), highlighting only the most important spatial patterns and dominant constraints.

For instance, we will describe that the BLA shape is the same for clay and silt+clay, including concluding remarks.

And yes, some parts, including L 545- 550, will be moved to the discussion section.

We will also revise the corresponding text, giving attention to Figure 10, removing unnecessary discussion.

- Lines 365–375 devote considerable time to comparing variability in measured SOC values and attainable values. I understand that some comparison is useful as it shows that the attainable values are consistently higher than measured SOC. However, it is unclear why the variability itself is important and how variability in the true values and the attainable values is directly comparable. The interpretation and significance of this result should be clarified.

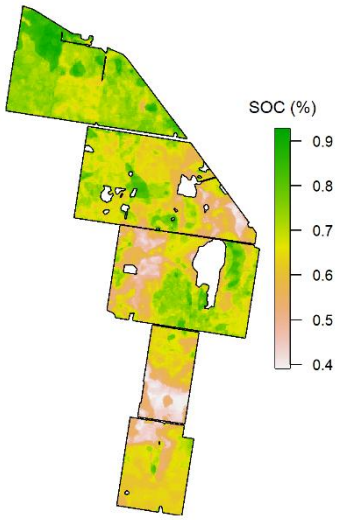
Response: Thank you for this comment. We have revised the statement concerning variability. Rather than referring to "narrower variability," we now state that the measured SOC distributions showed greater interquartile ranges than the attainable SOC estimates obtained from the BLA models.

Proposed text: *Figure 5 compares measured topsoil SOC with attainable SOC estimated from the rainfall-region-specific BLA models using data from the 72 grain-growing farms. For each sampling point, the measured value of each soil property was entered into the corresponding BLA model for that rainfall region. The SOC value predicted from the fitted upper boundary was considered the attainable SOC for that predictor. These estimates were then grouped by rainfall region and soil property to construct the boxplots. Across the rainfall regions, attainable SOC was generally higher than measured SOC, indicating a consistent gap between current and attainable SOC levels. However, the magnitude of this gap varied among rainfall regions and soil properties. The measured SOC distributions also generally showed greater interquartile ranges than the corresponding attainable SOC estimates."*

- Why is the SOC map not included in Figure 8? It would also be informative to include the sampling locations, if this information is not restricted.

Response: Thank you for this comment. We have added the SOC map to Figure 8 to provide a more complete overview of the mapped soil properties. We will add the sampling locations without coordinating them since the farm data are privately owned.

The SOC map has been added to Figure 8 as follows



- L55–60: The specific values from Ma et al. (2023) do not appear relevant here. This study uses SOC content (%) and therefore the stock values does not provide comparable context. It would be more useful to include values expressed as SOC content from literature. Otherwise I suggest removing these values altogether.

Response: Thank you for this suggestion. We agree that the SOC values cited in this section should be directly comparable with the SOC metric used in our study. We reviewed Ma et al. (2023) and confirmed that the optimum SOC values reported for maize, wheat, and rice are SOC concentrations expressed in g kg^{-1}, rather than SOC stocks. We have therefore converted these values to percentages (10 g kg^{-1} = 1%) and revised the text accordingly. We have also clarified the terminology to avoid confusion between SOC concentration and SOC stock.

In the Ma et al. (2023) paper**,** page 3 (pdf page) “The causal effects of SOC and fertiliser on yield”

In the first paragraph under this heading, the paper states that yield levels off at an “optimum SOC concentration”. In the same paragraph, it then defines optimum SOC as “in grams of organic carbon per kilogram of soil”, and reports values in g kg^{-1} for maize, wheat, and rice

Comments concerning grammar, structure, and presentation:

General comments:

- "Topsoil" is consistently followed by "(0–30 cm)" throughout the text, repeated approximately 15 times. As this is a standard depth range for topsoil, it is sufficient to state this once, including in the abstract. The same applies to subsoil depth ranges.

Response: Thank you for this suggestion. This has been checked throughout the article, and the unnecessary corresponding depth range has been removed once it is defined as topsoil and subsoil.

> I attempted to point out most grammatically incorrect sentences, but there are likely more. I would like to encourage the authors to proofread their work carefully, as in its current form the writing does not meet publication standards. I would also advise to remove filler phrases that increase word count without adding scientific content (e.g., L180: “and illustrate the varied climatic gradients that influence Australia's agroecosystems”).

Response: Thank you for highlighting this issue. The manuscript has been carefully revised to address grammatical errors and improve the clarity and readability of the writing. Unnecessary and repetitive wording has also been removed, including the phrase identified in Line 180.

Abstract:

- "BLA model" → "BLA models"

Response: Thank you. This has been corrected.

- The following two sentences largely repeat the same information, and the connective "next" is not appropriate in context. These should be rewritten:*"Digital soil maps for each soil property for a case study farm in the Wimmera, Victoria, were used to illustrate how the BLA can be used to identify limiting factors at the within-field level. Next, we applied the developed BLA models to that case study farm to determine the attainable SOC at the farm scale across six key soil properties."*

Response: Thank you for this comment. The text has been revised to avoid repetitive information and to remove the inappropriate “next” to improve flow and clarity.

Proposed text: *“The developed BLA models were applied to a case-study farm in the Wimmera region of Victoria using digital maps of six key soil properties. This enabled the estimation and mapping of the attainable SOC and its limiting soil factors at the within-farm scale.”*

Introduction:

- L105: "*This process involves fitting a line to the data cloud edge, which is often the upper part (Hajjarpoor et al., 2018)."* — This sentence could be tightened, as it is informal and imprecise.

Response: Thank you for this comment. The sentence has been revised.

Proposed text: *This process involves fitting a line along the upper boundary of the data distribution, which represents the edge of the observed data cloud (Hajjarpoor et al., 2018).*

- L105: "*This 'boundary line' indicates the maximum yield, also often referred to as yield potential, under a condition when a parameter of interest lies on the x-axis*." — Referring to an x-axis without a figure is quite confusing to the reader. I recommend a clearer explanation.

Response: Thank you for the suggestion. The sentence has been revised to remove the confusing reference to the x-axis and to provide a clearer explanation.

Proposed text: *"This boundary line indicates the maximum yield, often referred to as yield potential, for a given value of the parameter of interest."*

- Materials and Methods:
- L180: Please provide a reference for the dataset, instead of a link in the main text.

Response: Thank you for this suggestion. We have removed the webpage link from the text and replaced it with a formal citation to the Australian Bureau of Meteorology's seasonal rainfall classification. The bibliography has also been added to the reference list.

Proposed text: *"Accordingly, the 72 farms were classified into six categories (Figure 2 and Table 1) based on the Australian Bureau of Meteorology's (BOM) seasonal rainfall zones (BOM, 2026) in order to capture this climatic influence."*

Reference-list entry:

> *Bureau of Meteorology, 2026. Climate classification maps: Seasonal rainfall zones. Australian Government, Product code IDCJCM0006. Available at: https://www.bom.gov.au/climate/maps/averages/climate-classification/ (accessed 29 July 2026).*

- L220: "attainable SOC" → "maximum attainable SOC"

Response: Thank you. This has been corrected

- Section 2.41 discusses only outlier removal, please chang the title accordingly

Response: Thank you for this comment. The title has been revised to **"**Outlier detection and removal."

- L235: The brackets in the equation should be enlarged. The i in Q_i should be a subscript.

Response: Thank you. The equation has been revised accordingly.

- L245: *"Nevertheless, this approach takes a lot of effort and time-consuming, particularly when dealing with big datasets."* — Please fix the grammar. Please clarify what you mean by "looking at the data cloud" in the previous sentence.

Response: Thank you for this comment. The grammatical error has been corrected. “looking at the data cloud” has been clarified as visually inspecting the upper boundary of the observations representing attainable SOC.

Proposed text: *The most straightforward method for identifying data points that represent attainable SOC at a given predictor value is to visually inspect the upper boundary of the scatterplot, or data cloud. However, this manual approach is labour-intensive and time-consuming, particularly for large datasets.*

- "Outlier = TRUE if $D_m > Q_i$; otherwise, Outlier = FALSE" should be removed, as it is not a mathematical expression and does not aid understanding. Just including "$D_m > Q_i$" in the text would be better.

Response: Thank you for your comment. This has been removed and included $D_m > Q_i$ in the text.

Proposed text*: More specifically, observations with Mahalanobis distances exceeding the Qi-th percentile ($D_m > Q_i$) could be classified as outliers and subsequently removed from the analysis*

- The brackets in Equation 2 should be enlarged to fully cover the fraction.

Response: Thank you. Corrected.

- L370: "*smallest BLA among"* should be changed to *"lowest attainable SOC estimate among."*

Response: Thank you. We have changed accordingly.

Proposed text: *The minimum attainable SOC (MinASOC) is the lowest attainable SOC estimate among the 6 predictors, and the maximum attainable SOC (MaxASOC) is the largest BLA among the 6 predictors.*

Results:

- L320: "study farms" → "study farm"

Response: This has been corrected.

- L425: "physiologically" is not the right term here.

Response: Thank you for this comment. We agree that “physiologically” was not appropriate in this context and have replaced it with alternative phrase.

Proposed text: *The findings are consistent with established soil chemical processes: ,,,,*

- L400: "results of the boundary line" → "resulting boundary line" or "results of the BLA"

Response: The manuscript has been revised accordingly.

- L495: "firm" → "farm"

Response: Corrected

- L500–505: *"The accuracy of predicting SOC was consistently moderately good across all layers (CCC = 0.64–0.74, NNSE = 0.68–0.74), and almost no bias."* — Please fix the grammar.

Response: Thank you for this comment. The sentence has been revised to improve its grammar and clarity.

Proposed text: *"SOC prediction accuracy was consistently moderate to good across all soil layers (CCC = 0.64–0.74; NNSE = 0.68–0.74), with almost no bias."*

- L620: *"However, the SOC gains if these subsoil limiting factors are removed were not illustrated (similar to Figure 10c for topsoil) because soil amelioration is very hard, and mostly impossible at depth."* — Please fix the grammar.

Response: Thank you for this comment. The sentence has been revised to improve its grammar and clarity.

Proposed text: *However, the potential SOC gains resulting from alleviating these subsoil limitations were not illustrated, as was done for topsoil in Figure 10c, because soil amelioration at depth is generally difficult and, in many cases, impractical.*

Figures and Tables:

- Explaining the BLA abbreviation beneath each figure seems redundant.

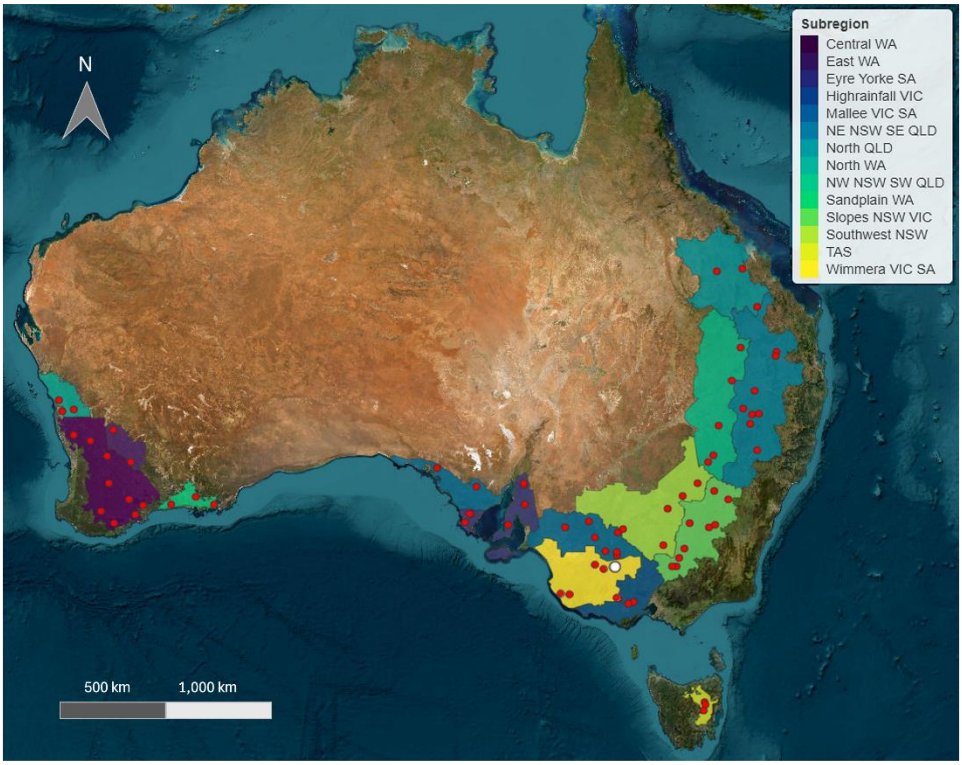
Response: Thank you for your comment. We think defining abbreviations within captions is also standard scientific writing practice.

- Figure 1: Why not just highlight the specific farm used in the case study in white? It is already clear from the yellow color which one is the Wimmera VIC SA. If the location

of the specific farm is classified, then I suggest just coloring these points red as well. This representation is confusing and suggests that all of these white points were used as case study farms.

Response: Thank you for this suggestion. We agree that the previous colour scheme could be misinterpreted as indicating multiple case-study farms. Figure 1 has therefore been revised so that only the specific farm used in the case study is highlighted in white, while the remaining farm locations are shown in red. This change clarifies the distinction between the case-study farm and the other sampled farms.

The revised Figure 1 is as follows



- Table 1: Consider removing the Classification ID column altogether.

Response: Thank you. Classification ID column has been removed.

The revised Table 1 is as follows:

Rainfall region	***Soil sample sites***	***No. of farms***
Summer 350-650 mm	*324*	*13*
Uniform 500-800 mm	*183*	*8*
Uniform 250-500 mm	*75*	*3*

Winter 250-500 mm	*225*	*9*
Winter dominant 500-800 mm	*300*	*12*
Winter dominant 250-500 mm	*675*	*27*

- Table 2: The formatting needs some attention. Word spacing in the first column should be corrected. Maybe replace "Soil landscape grid" with "terrain derivatives." Resolution information should be moved to a separate column. A data source for proximal sensing is also missing.

Response: Thank you for your suggestions. The table has been substantially revised. The data source for proximal sensing will be added.

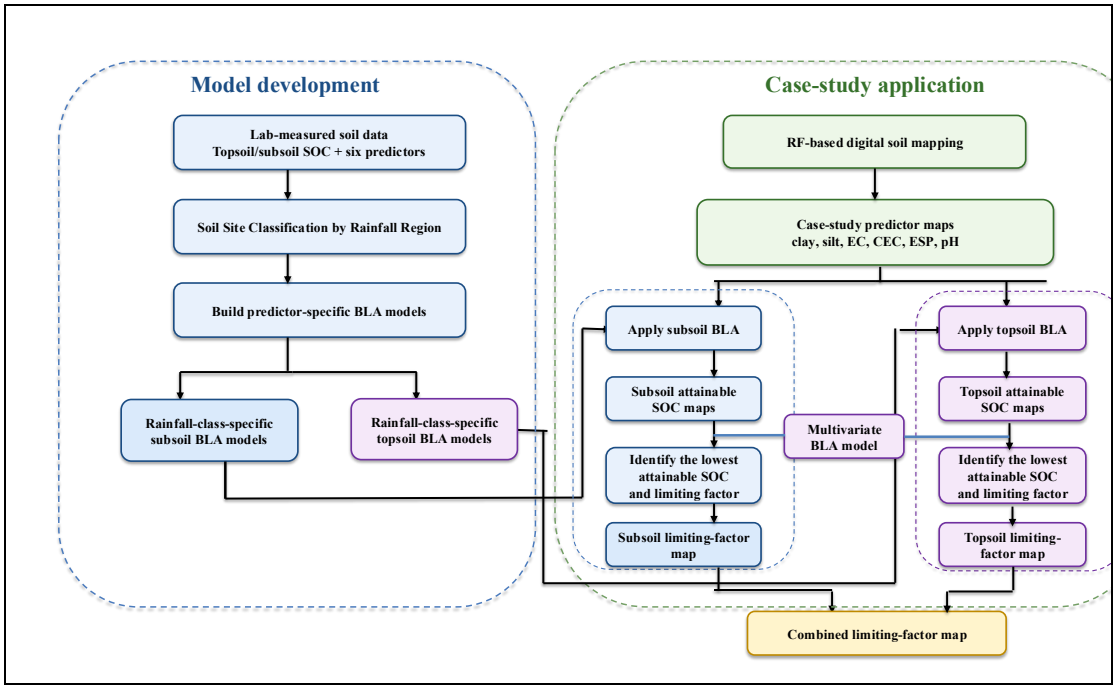
Proposed Table 2 is given below:

Layer description	Layer type	Product details	Resolution
Barest earth satellite imagery	Remote Sensing	Geoscience Australia 30-year Landsat satellite imagery compilation of barest surface conditions - representative of long-term topsoil condition (Roberts et al., 2019).	30 m
Aerial radiometric map	Aerial gamma radiometrics	Geoscience Australia radiometric map of Australia - shows airborne measured potassium, uranium and thorium (Minty et al., 2009).	100 m
Digital elevation map	Terrain attributes	SRTM-derived (Shuttle Radar Topography Mission) 1-arcsecond digital elevation model (Gallant et al., 2011)	30 m
Terrain derivatives of Australia	Terrain attributes	Soil and landscape grid of Australia derivative terrain covariates - slope (%), topographic wetness index (TWI), multi-resolution valley bottom flatness (MrVBF) (Grundy et al. 2015; Malone et al, 2025)	30 m
Electromagnetic survey	Proximal Sensing	Interpolated proximal electromagnetic induction survey map	10 m
Radiometric survey	Proximal Sensing	Interpolated proximal gamma radiometric survey map	10 m

- Figure 3: This flowchart would benefit from significant revision. One dashed box contains a single element and is therefore redundant. "Develop six BLA models" does not connect to the resulting topsoil and subsoil BLA models. The arrows pointing to "Six attainable SOC maps (subsoil)," "Six attainable SOC maps (topsoil)," and "Multivariate BLA model" do not have a starting point. The flowchart should be restructured to show only the key logical steps in the correct order and with correct relationships. The flowchart could also be better utilised in the main text.

Response: Thank you very much for these comments and suggestions. We have removed the redundant dashed box containing a single element and substantially revised Figure 3 to clarify the analytical workflow. The revised figure now distinguishes between model development and case-study application, showing how rainfall-class-specific BLA models were developed separately for topsoil and subsoil and subsequently applied to the corresponding soil predictor maps of the case-study farm. The multivariate BLA model was then used to identify the lowest attainable SOC estimate and the associated limiting factor.

The revised figure is given below:



- Figures 4 and 6 are low resolution and should be improved.

Response: Thank you for this comment. The original figures were generated in R at high resolution; however, their quality may have been reduced during insertion into the Word document. The original high-resolution figure files will also be provided separately during submission, in accordance with the journal's figure requirements.

- Figures 5 and 7: The top value on the y-axis occasionally overlaps with the upper plot boundary, I would suggest placing it outside the plot. The legend should use descriptive labels ("Attainable SOC," "Measured SOC") rather than programmatic variable names.

Response: Thank you for the suggestion. The figures regenerated correctly and were replaced in the manuscript accordingly.

- Table 3: A clearer description of how these values were obtained would be useful. Specifically, whether they represent the mean of the entire dataset or a subset. If it's for the whole dataset, then please explain the rationale behind averaging attainable SOC across all subregions.

Response: Thank you for this comment. The statistics presented in Table 3 were calculated using the entire dataset across all 72 farms. We have clarified this in the revised manuscript. The purpose of reporting the overall mean, median, minimum, and maximum values was to provide a broad summary of the measured and attainable SOC concentrations across the Australian grain-growing regions. These values are intended to describe the overall distribution and potential range of attainable SOC, rather than to imply that a single attainable SOC threshold applies uniformly across all rainfall regions. Regional differences are presented and interpreted separately elsewhere in the manuscript.

- Figure 8: Label placement and font size are inconsistent and should be standardised.

Response: Thank you for this comment. The label placement and font sizes in Figure 8 have been standardised across all panels to improve consistency and readability.

- Figure 9: Labelling is inconsistent and in some cases repeated (e.g., (b) appears both above and below the plot). The top row of plots are not aligned. The variable notation "SOC_{att}" is not explained and does not appear in the text, so please change the titles to something more descriptive.

Response: Thank you for the suggestion. The relevant changes have been made accordingly.

- Figure 10: I suggest removing subplot (c), as the SOC gain is the more informative metric. The "SOC_{att} " notation should also be revised here.

Response: Thank you for your suggestions. Yes, we will remove subplot (c) as subplots (c) and (d) provide similar information. The notion "SOC_{att} " will be revised.

- Tables 6, 7, 8: These tables could be removed altogether. The maps combined with relevant area percentages stated in the text would be sufficient.

Response: Thank you for this suggestion. We agree that the three separate tables were excessive. However, the area percentages provide an exact quantitative comparison of the soil properties limiting SOC accumulation, which cannot be readily obtained from the maps alone. We have therefore consolidated Tables 6 and 7 into a single, concise table comparing the topsoil and subsoil, which retains the key quantitative results.

The proposed adjusted table is given below:

Limiting factor	***Topsoil area (%)***	***Subsoil area (%)***
EC	*25.12*	*26.27*
CEC	*7.99*	*9.57*
ESP	*32.86*	*2.45*
pH	*0.31*	*0.41*
Silt + clay	*33.72*	*61.30*
Total	***100.00***	***100.00***