

Response to the Editor:

Dear Editor,

We are glad to hear that the reviewers have noticed a significant improvement in the manuscript after our major revision. However, both reviewers have raised additional comments. We are grateful for these and for the opportunity to re-submit a revised version.

We are sorry about not having been able to satisfactorily address the major criticism reviewer 2 raised in the first review concerning a supposed mismatch between the title, the introduction and the results / discussion of the manuscript. We believe we have fully addressed these concerns in this version and the other comments from reviewers 2 and 1. Most notably, we have changed the title of the manuscript to remove the aspect of 'drivers'. We also expanded the explanation of additional indicators in the introduction (soil organic carbon, soil erosion, infiltration capacity, vegetation, etc). We have now added hypotheses, as requested. We have expanded the section on the LDSF as well. Finally the discussion on the utility of these indicators for assessing soil degradation has now been included in the discussion..

We are very grateful to the reviewers for the effort and time in reviewing this manuscript. Their comments and inputs have been very valuable for us and have helped improve the original manuscript's quality. The response to each of the individual comments is below.

Thank you,

Leigh Winowiecki

I. Comments and Response: Reviewer #1

R1 C1: I highly suggested that the authors re-read the manuscript carefully and correct minor issue with tense (i.e. "is" vs "was, etc.), grammatical errors, and typos, which are minor but scattered throughout the manuscript. (Editor: Agreed. Please go through the MS top to bottom before re-submitting and check for consistency in writing)

Thank you for pointing this out. We have now gone through the manuscript in detail and edited it to ensure consistency in the use of verbal tenses. We have also corrected other minor grammatical mistakes and typos.

II. Comments and Responses: Reviewer #2

R2 C1: In the response letter, the authors did not really indicate how they have addressed my major criticism. (Editor: I noticed that the response letter from the last round was quite brief in

this regard. Please explain in your response letter in detail how you address these issues and where to find your changes in the document. Bring examples if changes were done throughout the manuscript and not just for a specific issue. Please also explain in the response letter more explicit why certain comments can be ignored / do not need to be addressed in the extent suggested by the reviewers.

Our apologies for not adequately addressing these issues in the previous response letter. We have included a track changes document whichs shows where specific changes were made, as well as a letter to the editor with a general response on the changes and a detailed response to each comment outlining how each comment was addressed. We hope this provides sufficient details on how we explicitly addressed each of the reviewers' comments.

We have modified the title to remove the aspect of drivers and to more accurately reflect the content of the manuscript. The new suggested title is, "Assessing soil and land health across two landscapes in eastern Rwanda to inform land restoration activities". This is a direct response to the reviewer's comment that drivers were not addressed and that the title did not reflect the context of the manuscript. We hope the reviewer and editor are satisfied with this change.

In the abstract we have now added these two sentences to further clarify the objective of the paper., "These data demonstrate the importance of assessing multiple biophysical properties in order to understand land degradation, including the spatial patterns of soil and land health indicators across the landscape. By understanding the dynamics of land degradation and interactions between biophysical indicators, we can better prioritize interventions that result in multiple benefits, as well as assess the impacts of restoration options."

We have expanded the introduction to include the explanation of the additional soil health indicators. In the original version, we focused on SOC, however as mentioned by the reviewer, we also included a number of biophysical variables to provide a more complete assessment. Specifically we included a description of the importance of considering multiple variables including, SOC, erosion prevalence, vegetation structure, tree density and species diversity, topsoil field-saturated hydraulic conductivity (a proxy for steady-state infiltration capacity), soil texture, pH and exchangeable bases. These additions were made to satisfy this comment from the reviewer "However, the authors did not introduce the various indicators of soil health and land degradation including interactions between them."

R2 C2: The authors did not study drivers of soil organic carbon although indicated in the title. (Editor: Agreed. The manuscript is rather on SOC and other soil parameters as an indicator for a specific soil status and soil health in general, but not focused so much on the aspects of drivers as suggested by the title)

We understand the reviewer's concern that there was a mismatch between the title, the introduction, results and discussion section in the first version of the manuscript, and that perhaps the original title was not adequately reflecting the full scope of the study, as it was referring to drivers of SOC only. This concern has been addressed in detail in C1. Yet, we disagree with the reviewer's opinion that we did not study drivers of SOC, but we do agree that this was not the sole focus of the study. While our data clearly demonstrate the control of sand content on SOC, as well as the impact of vegetation structure on SOC, we have also included a number of other key indicators. Therefore, we have changed the title to "Assessing soil and land health across two landscapes in eastern Rwanda to inform restoration activities".

R2 C3: I do not see that they expanded the section on drivers of SOC as indicated in the response letter. (Editor: Indeed, aspects of soil degradation and consequences for restoration were explained much better now. but I do agree that the section on drivers should give a broader picture still to guide the reader and put results into perspective).

We have changed the title of the manuscript to more accurately reflect the content. Specifically, we have eliminated the aspect of drivers. Therefore have not elaborated on the drivers of SOC but instead elaborated on the various indicators to be used when assessing land degradation and prioritizing restoration actions.

R2 C4: In the introduction the authors discussed the shortcomings in the assessment of land degradation and restoration very correctly (starting in line 62) and they introduced SOC as a universal / key indicator. In the next paragraph (starting in line 75), the authors addressed different indicators without given any explanation what indicators they have in mind. That illustrates one of the shortcomings of this manuscript. In the introduction the authors imply that only one universal indicator is used, however, that is not the case giving the variety of different indicators they analyzed. (Editor: I agree that the introduction is only in parts aligned with what later is analyzed and presented. More information and guidance for the reader to arrive at what you describe the study will do in l. 117 and following is needed and this should include a brief description of the other indicators you plan to look at).

We agree with the reviewer that the other indicators measured as part of the LDSF and included in this study need to be introduced here. We have now done this briefly in the introduction section in two different paragraphs (in one, we name all the indicators included in the study, and in the other, we give a brief intro about the most relevant ones).

Lines 86-88 we added "We argue that a coherent set of indicators collected using consistent measurement methods is needed to address the completely of ecosystem function."

In addition to the mention of SOC and erosion we added the below from lines 93 to 118

“In addition exchangeable base cations provide a measure of available nutrients and soil pH provides a measurement of potential constraints such as acidity. Land cover and vegetation structure play a key role in terms of driving soil organic carbon dynamics in landscapes while also influencing land degradation processes such as soil erosion. Therefore, indicators such as tree density within various vegetation structure classes and overall tree diversity provide useful information for informing restoration interventions around reforestation (Di Sacco et al., 2020). The use of carbon isotopes provides further insights on vegetation shifts as $\delta^{13}\text{C}$ values in the soil reflect the photosynthetic pathway of the aboveground vegetation (Boutton et al. 1998). Soil infiltration capacity is another well-established indicator of soil health, in particular of the soil's physical status and its hydrological functioning (Allen et al., 2011). Soil infiltration capacity influences the recharge of soil and groundwater stores and the generation of surface runoff, with implications for erosion and flooding occurrence (Hillel, 1998).”

R2 C5: I would expect from the manuscript an introduction / motivation of the used indicators as e.g. vegetation composition, tree density, species diversity, hydraulic conductivity, ^{13}C . Unfortunately, that was not done. The authors should also decide whether SOC is an inherent soil property (e.g. line 123) or controlled by inherent drivers. (Editor: agreed)

We have expanded the introduction on the use of various indicators. See above comment and lines 93 to 118

In the introduction we also state, “However, ecosystems are complex and multiple biophysical and socio-economic factors need to be considered when targeting, planning, implementing and tracking restoration on the ground.” We have also expanded on the various indicators used to both assess land degradation and prioritize land restoration activities.

Furthermore, we have cleared up an mis-understanding around SOC. For example by stating, “We assessed the relationship between inherent soil properties (such as texture) and SOC,...

R2 C6: After a thorough introduction of the indicators, I would expect hypotheses related to these indicators and how they might be interrelated. (Editor: Agreed. The formulation of testable working hypotheses related to your objectives as listed in I.120-122 and the data you want to use for that would be important and quite helpful for a reader).

We have now added these from lines 163

“Specific objectives of this study were to: 1) Assess soil and land health indicators across two landscapes; 2) Identify biophysical constraints; 3) Develop maps of soil erosion hotspots and variations in SOC for restoration interventions, based on the hypothesis that remote sensing (spectral) data can be used to predict erosion and SOC. We also assessed the relationship between inherent soil properties, such as texture, and SOC, the hypothesis being that factors such as sand content create constraint envelopes in terms of variations in SOC. Another hypothesis addressed in the study was related to whether there is a positive effect of SOC on

field-saturated hydraulic conductivity when we consider data from across diverse landscapes. We also assesses the influence of other soil properties on field-saturated hydraulic conductivity, in addition to human-induced processes such as soil erosion. Finally, we assessed the current status of vegetation structure across the landscape, in addition to tree density and tree species diversity, and conducted spatially-explicit assessments of SOC for eastern Rwanda.”

R2 C7: The general approach of the used framework (LDSF) has not been explained in detail although being decisive for the whole manuscript. I think it is much more than just the field sampling design. (Editor: I tend to disagree with this comment. LDSF has been described in the cited publications in great detail. However, the reviewer has a point. I think the fact that the manuscript does rely heavily on LDSF justifies to add a few extra lines on the motivation behind LDSF and how it relates to the study at hand).

We greatly expanded the methods section, including a detailed description of the various measurements made within the LDSF in the first revision. In the current version we have added a paragraph in the methods from lines 320-325 “The rationale behind the use of the LDSF in the current study was that it has been applied across a wide range of landscapes in the global tropics and has been shown to be robust in terms of assessing soil and land health in landscapes. It uses a standardized set of indicators that are consistently sampled and quantified, allowing for comparative studies between sites or landscapes. Also, the LDSF has been successfully applied in other studies for the mapping of indicators of soil and land health when used in combination with remote sensing satellite data (Vågen and Winowiecki, 2019, Vågen et al., 2013b).”

R2 C8: In the discussion, the reader of the journal would expect an evaluation how useful these indicators are in assessing soil degradation. This part is too superficial. (Editor: Agreed. A thorough analysis of the usefulness but also the limitation and uncertainties related to the use of the suggested soil health indicators would strengthen the discussion greatly. Especially if it can be related to a case study such as the one presented here).

We have added a discussion on the limitations and the usefulness on these indicators. Specifically from 676:

“Land degradation and restoration of degraded lands are complex processes that cannot be addressed effectively without considering multiple factors determining soil and land health. In this study we have assessed multiple indicators that can be readily quantified, and are widely accepted as important in determining soil and land health. Further, we used a sampling design that allowed us to measure these indicators consistently. This is critical for the design of interventions that target multiple aspects of land restoration, including soil erosion, species diversity and SOC. Specifically, this study identified low tree diversity and high occurrence of exotic timber species, highlighting an opportunity to explore the inclusion of indigenous tree species in both landscapes. In addition, maps of soil erosion will be used to target soil water

conservation measures to curb soil erosion. We argue that assessing these multiple indicators within a robust yet rapid sampling design will improve the effectiveness of restoration interventions as well as provide a baseline for tracking progress overtime.”

Additional note.

We have added the missing references as well.