Response to reviewer comments: On Soil health and the pivotal role of proximal sensing, by Hu et al.

We thank the reviewer for their review and comments. Below, we provide our responses in blue text.

Reviewer 1

Some sections, particularly in the abstract and introduction, contain lengthy sentences that could be streamlined for better readability.

Although various frameworks and sensor technologies for soil health assessment are mentioned, a more in-depth comparative analysis of the different technologies and methods would be beneficial. The authors should integrate a detailed discussion on the advantages, limitations, and specific applications of each sensor.

The manuscript briefly touches on policies related to soil health but lacks a deeper discussion on the practical challenges of implementing these policies, particularly regarding the integration of sensor technologies in large-scale soil management. A discussion on policy gaps and recommendations for improvement would add value.

The review highlights the potential of sensor-based methods but does not sufficiently discuss their limitations, such as cost, accessibility, and calibration challenges.

Throughout the manuscript, terms such as "soil health," "soil quality," and "soil function" appear interchangeably. Clarifying their distinctions and ensuring consistent usage would improve coherence.

Authors:

- We will revise the manuscript and focus on improving readability by shortening sentences and avoiding duplication.
- Figure 4 (sensor table) compares the sensing systems that are most currently applicable for soil health assessments and their capabilities for measuring indicators. We provided comprehensive citations to other works that already provide detailed descriptions and discussions on the advantages and limitations of the technologies (e.g., Soriano-Disla

et al. (2014); Kuang et al. (2012); Viscarra Rossel et al. (2011); Silvero et al. (2023); Adamchuk and Rossel (2010)). We'll ensure that we capture the limitations of the sensors in the revision, but will try to avoid excessive repetition of what has already been reported in the literature. We also view our paper as a means to guide the author to relevant papers in the vast and overwhelming volume of literature on this particular subject.

- We provided a discussion on global policies related to soil health; however, we will improve this text to emphasise how soil sensing might affect their implementation. There is a current tendency to focus policies on management measures that are supposed to have a positive impact on soil health. However, without documentation that includes specific measurements of soil health indicators and corresponding threshold values, it is impossible to judge such measures. The principal advantage of sensing methods is the ability to generate a large amount of data in a short time at a reasonable cost. Classical laboratory methods did not allow these types of judgements, and the soil health concept remains attractive in principle but undefined. That's why the introduction of a framework focused on ecology, with sensing at its core, is essential to make soil health an operational concept with real impact in the political and societal debate.

- We will ensure that limitations and costs of the sensing systems are more clearly articulated in the revision. As indicated above, this is essential to create operational procedures that can be applied in practice, a key requirement for achieving societal and political relevance.

- It is incorrect to state that "soil health," "soil quality," and "soil function" are used interchangeably in the manuscript. In Sections 2, 9, and Figure 2, we describe each term and its relationships. Indeed, the soil science community would be well advised to avoid confusion about terminology. The use of the term 'soil health' is appealing because it allows for comparison with human health, facilitating effective communication with the general public.

Abstract (Lines 1-16): The abstract summarizes the study well, but it lacks an explicit mention of the originality of the approach. Adding a sentence that highlights what makes this review unique would help clarify the contribution of the article.

Authors: Thank you for the comment. We thought the abstract was clear, but we will revise it to more strongly emphasise the uniqueness and timeliness of our manuscript. In doing so, a key element will be the connection of technical aspects of the various methods, which have already been described by others, albeit less comprehensively, with the policy arena, emphasising that this modern technology is crucial for introducing an operational soil health concept to the real world.

Introduction (Lines 17-63): The introduction provides a solid background on soil health but delays presenting the research problem. Consider introducing the core problem earlier.

Lines 39-50: The discussion on soil health policies could be expanded to critically analyze their limitations.

Lines 54-63: The transition to technological advancements is abrupt. A smoother connection explaining the shortcomings of existing assessment methods would help justify the focus on sensing technologies

Authors: As per our previous response, we propose to revise the introduction to emphasise the uniqueness and timeliness of our manuscript. Therefore, we'd prefer to maintain our current structure in the introduction, as it is essential to establish the broader context and significance before the research aims. We will revise the text related to policy to improve it in line with what was mentioned above. When revising, we will improve the readability between all sections of the manuscript, and particularly the one mentioned.

Objectives (Lines 64-68): The objectives are clear but could be more specific in addressing identified research gaps. Consider refining Objective 1 to specify key limitations in current assessment methods. Objective 3 should explicitly mention the practical applications of sensing technologies

Authors: Thank you for commenting that our objectives are clear. We agree. We will be more specific in identifying current gaps and limitations while focusing on the major potential

of practical applications for the policy arena as discussed above.

Defining Soil Health (Lines 69-100): The historical context is well presented but contains some redundancy. Streamlining this section would enhance readability. The manuscript presents multiple definitions of soil health but does not take a clear stance. A brief discussion on the preferred interpretation would improve coherence.

Authors: Thank you for noting that the historical context is well presented. We will revise the section to improve readability. We described the progression in definitions from soil fertility to soil quality to soil health, and we believe that our stance is clear: we propose that soil health must encompass an ecological focus that emphasises ecosystem functions, not only anthropocentric services, and that modern sensing is essential to produce results in everyday practice.

Limitations of Current Definition (Lines 104-133): The section provides a comprehensive overview of the challenges associated with defining soil health. However, consider streamlining the discussion to eliminate redundancy and enhance clarity. A brief critique of the varying opinions on the necessity of the soil health concept could strengthen the argument for a more objective definition.

Authors: Thank you for noting that our overview is comprehensive. As mentioned previously, we will improve the writing to remove duplication. Regarding the referee's comment on the critique of varying opinions on the necessity of soil health, we have already addressed this (lines 125-132) by citing relevant literature and by clearly stating our position that the concept remains valuable despite criticisms. We provide specific examples of its contributions to science and communication. Since our paper's objective is to improve soil health assessment rather than debating the concept's fundamental necessity, an extensive discussion of this debate is outside the scope of our paper. But we certainly agree that the concept of soil health should be clearly defined as a starting point for any discussion.

Current Soil Health Assessment Frameworks (Lines 134-157): While Table 1 summarizes the different assessment frameworks, this section could be enhanced by a more critical analysis of

the differences between these frameworks and their applicability to different regions or context.

Authors: Table 1 provides a comprehensive comparison of eight key aspects (status, land-use context, scale, adaptability, sampling methods, indicator selection, interpretation, and integration approaches), which represents a systematic and critical analysis of the differences between the frameworks. The subsequent discussion explicitly addresses regional and contextual limitations, and we further critically examine the lack of standardisation and consensus, particularly outside agriculture. Subsequent sections on indicators, measurement, and interpretation also provide a critical analysis of these within specific frameworks. We believe that all the elements you mention are present, but agree that the text can be more specific so that we can move on to the core of the paper, namely, the ability to finally assess soil health with new techniques—a critical element for policy and society.

A discussion on adapting these frameworks for non-agricultural ecosystems would also be valuable. The authors could discuss the scalability of these frameworks. Which ones are best suited for broad implementation, and which face barriers to adoption?

Authors: Thank you for the comment. We believe that the current comparison and discussion on existing frameworks is sufficient. A Discussion on how existing frameworks could be adapted for non-agricultural systems will significantly lengthen and complicate the already long manuscript without enhancing our main message. Regarding scalability, Table 1 systematically addresses this through the 'Scale' and 'Easily Adaptable to Larger Scales and Other Land-Use' columns, showing that most established frameworks operate at the field scale with limited adaptability, while emerging approaches, such as those by Su et al. (2018); Wade et al. (2022) address landscape and broader scales. An additional discussion might be redundant.

A clearer connection between the limitations mentioned (e.g., scale and applicability) and specific examples or case studies would enhance the depth of the discussion

Authors: We tried to establish a connection between the limitations of the frameworks to specific examples, in section 4, p.6, lines 140–153 in the original submitted manuscript. We

provided specific citations to support these limitations, and some of those provide case studies. We certainly agree with the reviewer that case studies are essential for conveying intended messages.

Soil Health Indicators (Lines 158-191): This section is well-developed, but it would be helpful to add a summary table of the 20 indicators mentioned to improve readability and understanding of the key points.

Authors: Thank you for noting that the section on indicators is well-developed. We agree. But we disagree that an additional table would improve the paper. Figure 4 seems to serve this purpose, showing 30 indicators (10 physical, 12 chemical, and 8 biological) along with the sensors that can measure them. An additional table would be redundant.

Measuring Soil Health Indicators (Lines 192-216): The section could benefit from examples of more innovative sampling strategies beyond those mentioned, illustrating advancements in the field. A discussion on the potential consequences of inadequate sampling methods on the interpretation of soil health assessments would provide additional context to the importance of robust sampling protocols.

Authors: We worry that a comprehensive discussion on innovative sampling strategies would require an additional manuscript. A substantial body of literature on soil sampling for soil fertility exists, which has been widely applied worldwide, including thorough statistical analyses. This can also apply to soil health sampling to make sure that the data are representative. Our discussion already identifies the fundamental limitations of some current approaches and references robust alternatives, such as the structured guidance provided by (Lawrence et al., 2020; Brus and De Gruijter, 1997). Regarding the consequences of inadequate sampling, we noted that methods without a robust design fail to accurately capture soil variability, resulting in biased and unrepresentative data that compromises all subsequent analyses and management decisions.

Interpreting Soil Health Indicators (Lines 217-260): The section on interpreting soil health indicators provides a solid overview but could benefit from a few adjustments: It would be

useful to explore the extent of bias introduced by ordinal scales and how it affects interpretation across different ecosystems.

Clarifying the limitations of assumptions, such as 'more is better,' could strengthen the argument, particularly in complex soil systems.

A discussion on challenges in model calibration and data collection for large-scale applications.

Authors: Thank you for acknowledging that this section is strong. For the first point about exploring bias from ordinal scales across ecosystems, we will clarify what we mean by 'introducing bias' on line 218 and provide an appropriate citation. However, a detailed exploration of this topic across different ecosystems would require an extensive analysis that is beyond the scope of this study. Regarding the second point on clarifying limitations of scoring curve assumptions, we did touch on this and provided references to other papers that discuss this issue comprehensively (see line 222, p. 9 of the original submitted manuscript). For the third point, we think the reviewer is referring to the soil-water-atmosphere-plant ecosystem model mentioned in lines 237–242. We appreciate that the reviewer raised this point, and we will address it in the revision.

A Soil Health Index (Lines 261-278): While discussing the limitations of composite indices, it would be beneficial to: Clarify how data-driven methods, like principal component analysis, can address non-linear interactions among indicators.

Consider a multi-tiered approach that combines composite indices with individual actionable indicators for more precise management recommendations.

Discuss how a balance between simplicity and scientific rigor can be achieved in practice, especially when communicating with stakeholders.

Authors: Regarding the use of PCA analysis for indicator integration. We apologise for our rather clumsy phrasing. PCA is a linear method, and when used on its own, it will not address non-linearities among indicators. We will clarify this in the revision. Regarding the second point about multi-tiered approaches, we addressed this point in the discussion (p. 11, ln 271). There, we noted that individual indicators provide actionable management insights while composite indices lack specificity. This is important because it can guide research on

indicators that need improvement. For the third point about achieving balance between simplicity and scientific rigour in stakeholder communication, we thank the reviewer for raising this valuable point. We will provide further discussion on this in the revision. Simplifying is crucial for achieving acceptance of procedures in practice; however, if these procedures are not scientifically sound, efforts may backfire. Simplicity is key when communicating with stakeholders. While the scientific rigour does not have to be communicated for simplicity reasons, it should be ensured in the background as a key responsibility of the scientists.

An Ecological Focus for Soil Health (Lines 279-311): It would be useful to define key terms like "soil health" and "ecosystem services" at the start of the section to avoid ambiguity. Strengthen the ecological perspective on soil health by including concrete examples of methodologies that could be applied in this framework.

Authors: We defined 'soil health' early in Section 2, and elaborated in Section 3. Does the referee mean that we should repeat the definition at the start of this section, too? This does not seem necessary. The text in this section builds on the stated definition. 'Ecosystem services' are defined according to Hassan et al. (2005), which is universally accepted and adopted.

Regarding the strengthening of the ecological perspective, in the submitted manuscript, we provided an example of how our proposed framework might be applied using the southern Alberta grassland example (Janzen et al., 2021). We aimed to demonstrate how our proposed value-neutral assessment framework would address the divergent outcomes resulting from different evaluative perspectives. Perhaps this was unclear? In the revision, we will ensure that these parts are enhanced to clearly articulate the application of our framework.

Sensing Soil Health (Lines 312-326): The section on sensor-based technologies should delve more into the challenges such as costs, calibration, and accessibility. Discuss how these limitations can be mitigated to make such technologies more viable for widespread use. If you mention sensor fusion, briefly explain how different sensors complement one another.

Authors: We've responded to this comment already. Please see above.

Sensor-based soil health indicators (Lines 327-344): Include examples of soil health indicators that can be measured with sensors. This will provide readers with a clearer understanding of the practical applications of these technologies. While the manuscript discusses the advantages of sensor-based systems, it would be beneficial to explore how current limitations, such as data quality or sensor calibration issues, can be addressed.

Authors: We provided soil health indicators that can be measured with sensors in Figure 4. Again, we've responded to this comment before. We will revise to emphasise the challenges of the sensing-based approach.

Sensing for characterising soil health (Lines 345-421): The manuscript discusses the potential of sensor technologies but lacks details on challenges such as cost, accessibility, and data interpretation. The section mentions sensor fusion but does not clearly explain how different methods complement each other. A brief clarification would be beneficial

Authors: The indeed important aspects of cost, accessibility and data interpretation have been discussed above, and we have reacted to it.

Conclusion & Future Directions (Lines 422-440): The conclusion summarizes key points well but could end with a stronger statement on policy implications and recommendations for future research. Consider adding a discussion on the practical steps needed to operationalize the proposed framework.

Authors: Thank you for acknowledging that our conclusion concludes well. As suggested, we will revise it to strengthen our final messages. What is needed now is real action in the real world. The new sensing techniques represent a paradigm shift, finally allowing the operationalisation of the soil health concept to the benefit of the effectiveness of environmental policy and, therefore, for society at large.

Suggestions for Improvement: Manuscript structure : o Reorganize certain sections to avoid repetition and make the article flow more smoothly. For example, a dedicated section on the challenges and limitations of sensing technologies could be added just after presenting the methods. o Ensure that the definitions of key terms like 'soil health,' 'soil quality,' and 'soil

function' are explicitly given in the introduction and consistently used throughout the article

Authors: Thank you for summarising your review. We have thoroughly addressed the comments made.

Inclusion of Real-World case studies: The article would benefit from the inclusion of real-world case studies or examples that demonstrate how sensor technologies have been successfully implemented in different agricultural settings. Case studies would help readers understand the practical implications of using these technologies and provide insight into how challenges such as calibration, data integration, and cost can be addressed in real-world contexts.

Authors: We appreciate the suggestion. We will provide an example in the revision to offer readers guidance on how to implement the framework.

Comparison Table: As mentioned earlier, a comparative table summarizing the strengths, weaknesses, costs, and typical use cases for the different sensor technologies would be an excellent addition. This would offer readers a clearer guide to choosing the right sensor technology based on their needs.

Authors: The information is in the submitted Figure 4, but as we have written above, we will revise according to the comments made.

Future directions: The authors briefly mention the integration of sensors with AI, but a more extensive discussion of future trends and research opportunities would strengthen the article. For instance, exploring the potential for integrating sensor data with other environmental data sources (e.g., satellite imagery, climate data) could provide more holistic insights into soil health

Authors: We agree that our discussion on this was a little brief, and we will revise to enhance these aspects. However, thorough reviews on sensors and AI, as well as the integration of sensing with remote sensing, already exist, and we have cited them, for example, (Silvero et al., 2023; Grunwald et al., 2015; Rossel et al., 2024).

Questions for the Authors:

Sensor calibration and soil type variability: How do you recommend dealing with the

variability in sensor readings when applied to different soil types and environmental conditions?

Data integration: What strategies do you suggest for integrating sensor data with other environmental data (e.g., weather, land use) to improve the accuracy of soil health assessments?

Authors: Thank you for the questions. We politely suggest that these aspects are somewhat peripheral to our manuscript and have been addressed in other literature on specific sensor systems and technical reviews on sensing. Some examples of integrating environmental data with sensing are presented in (Yang et al., 2019, 2022) and (Viscarra Rossel et al., 2010). There are others, of course. We suggest the reviewer seek out the suggested (and other) literature, or contact us separately, and we'd be glad to discuss and help.

Implementation in developing regions: Could you expand on the challenges and strategies for implementing sensor technologies in low-resource settings, especially in developing countries?

Authors: This is a good point. We agree that implementing sensing technologies in low-resource settings is highly relevant and will add a thorough discussion on how we might use our framework in such settings. Thank you for the comment.

7. Conclusion and recommendations

The manuscript provides a valuable contribution to the discussion on the use of sensor technologies for soil health assessment. However, to enhance its scientific impact, it is essential to clarify certain technical points, provide a more in-depth comparative analysis of the different technologies, and focus on the practical aspects of implementing these technologies for soil management. I recommend a major revision before publication.

Authors: Thank you for acknowledging the value of our manuscript. We will certainly revise according to the comments and our responses above. Thank you.

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