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

We thank the editor for the comments. Below, we provide our responses in blue text

Dear Yang Hu and Coauthors, Thank you for your comprehensive review on soil health assessments and the role of proximal sensing. While the manuscript addresses an important topic and presents valuable concepts, several significant concerns must be addressed before acceptance for publication. While both reviewers agreed that your manuscript presents an important topic, they both identified several issues that need to be addressed.

For instance, both reviewers noted that the manuscript emphasized the disadvantages of laboratory methods and advantages of sensors, without addressing their limitations, costs, or implementation challenges. They consistently noted the lack of concrete evidence, case studies, and quantitative comparisons to support the theoretical claims, as well as a disconnect between the ecological framework and sensing technologies that undermines the paper's central thesis. Additionally, both reviewers called for more technical specificity, better integration of concepts, and honest assessment of the substantial practical barriers to operationalizing the proposed framework, including standardization needs, calibration requirements, and real-world adoption challenges. These common concerns highlight that the aspirational vision presented in the manuscript currently lacks balanced evaluation, concrete evidence, and practical grounding necessary to support its claims about the operational readiness of sensor-based soil health assessments.

A fundamental weakness of this manuscript lies in its failure to demonstrate how sensing technologies specifically enable and enhance the proposed ecological framework for soil health assessment. The ecological approach (Section 9) and sensing technologies (Sections 10-12) are presented as disconnected parallel concepts rather than integrated solutions, with no clear mechanistic connection showing why sensors are uniquely suited to operationalize ecological soil health assessment framework. The proposed ecological framework appears entirely method-agnostic, failing to demonstrate why a sensor-based measurement approach is superior to traditional laboratory methods, thus failing to support the central idea that proximal sensing is pivotal to this framework.

While the manuscript extensively evaluates the limitations of current lab-based soil health indicators and assessment approaches (Sections 5-9), it fails to establish clear causal links between these identified problems and how sensor-based measurements specifically resolve them. For instance, you identify issues with indicator selection subjectivity, interpretation challenges, and integration difficulties in current frameworks, but do not demonstrate how sensing technologies fundamentally address these conceptual and methodological problems rather than simply providing alternative measurement approaches.

The manuscript contains numerous assertions about sensor benefits (rapid data collection, cost-effectiveness, spatial coverage) but lacks rigorous quantitative comparisons with conventional methods that would substantiate claims of superior performance for soil health assessment. Proximal sensing technologies face significant limitations that impede their operational deployment for soil property predictions, including the lack of standardized protocols that make it difficult to compare and validate approaches across different studies and geographic settings. While finer spectral and spatial resolutions are often pursued, they do not necessarily improve prediction accuracy and can lead to overfitting, and the requirement for extensive site-specific calibrations limits model transferability and scalability. The paper would be greatly improved by providing more discussion on the challenges and steps required to operationalize such a framework. For example, operationalizing many of these technologies would require the development of standardized hardware and software integration protocols (i.e., calibration transfer), validation frameworks for diverse soil-landscape conditions, cost-effective portable sensor systems, and methods to assess sensor interaction effects and compatibility across different measurement targets and sample supports. Additionally, sensor response consistency over time must be improved to minimize frequent recalibration needs, while extending capabilities beyond basic soil properties to dynamic biogeochemical indicators and integrative soil health indices that can better inform soil health assessments across varied soil systems. While significant process has been made over the past several decades, significantly more work is needed to implement your proposed framework. Additionally, as noted by Reviewer 2, the ecologically-based soil health assessment framework is underdeveloped and not clearly connected to the lab vs sensor-based measurement discussion.

While you discuss the benefits of evaluating soil functions vs human focused ecosystem services, it is not clear how you propose to quantify these functions from sensor measurements. Measuring soil processes and functions is incredibly complex and challenging and is the primary reason most soil health assessments focus on measuring soil properties and indicators. Integrative sensing offers a promising approach but requires a comprehensive sensor-based characterization of soil systems in different ecological states or conditions. In addition, you fail to adequately articulate why an ecological perspective on soil health inherently requires or benefits from sensor-based measurement approaches, leaving readers without a compelling rationale for the purported synergy between ecological frameworks and sensing technologies that forms the manuscript's core premise.

Both reviewers also suggested additional examples/case studies illustrating examples of sensor-based soil health assessments and additional review of relevant sensor technologies and how they can support the proposed framework. While I agree with your response that there is already a wealth of literature reviews on the various subjects addressed in this review paper, none of them, to my knowledge, specifically address the application of soil sensor for soil health assessments. Therefore, you should consider providing more concrete examples of how these soil sensor technologies have been used (or could be used) to assess soil health, describing both the documented strengths as well as their weaknesses. While soil sensing technologies hold considerable potential for improving soil health assessment, considerable work is still needed to operationalize these technologies. Adding references to Fig 4 (possibly as supporting materials) would help guide readers to the relevant sensor-specific literature.

In summary, your manuscript requires major revisions, and should addressing the following points:

**Authors:** Thank you for your constructive comments, detailed feedback, and summary. We have undertaken a substantial revision in line with your suggestions, and we believe these changes have significantly improved the quality of our paper. We appreciate your input.

1. Provide a clearer and more practical description of the proposed soil health assessment framework that addresses specific protocols, implementation procedures, indicator selection criteria, threshold establishment methods, and validation approaches.

**Authors:** To address this comment (and related feedback), we have substantially revised Sections 9 ('An Ecological Focus for Soil Health') and 10 ('Sensing Soil Health'), and have redrawn Figures 2 and 3. These revisions provide a clearer, more practical, and more detailed description of our proposed framework. Specifically, Section 9 has been refined to present a more precise and nuanced conceptual foundation, which is now directly linked to a revised Figure 2. Building on this, Section 10 has been restructured to outline a more explicit operational protocol, illustrated in the new Figure 3, and to describe in detail the procedures for implementing the proposed framework. To further strengthen these descriptions and to demonstrate the integration of sensing with ecological soil health assessment (also addressing point 3 below), we now include an example application scenario: one focused on mine-site rehabilitation, which is currently a major global problem. The example guides the reader step by step through the practical implementation of the framework.

2. Present balanced technical comparisons that honestly discuss sensor limitations (costs, calibration requirements, standardization challenges) alongside advantages, while addressing laboratory method strengths as well as weaknesses,

**Authors:** We have revised Section 11 ('Sensing for Characterising Soil Health') and added a new subsection and table (Table 3), which succinctly summarise the advantages, limitations and potential solutions for sensing-based soil health assessments. They explicitly outline current limitations of soil sensing, including initial costs, calibration requirements, reliance on conventional laboratory analyses, and the need for standardisation protocols. In the revised text, we also provide a more balanced discussion that acknowledges both the strengths and weaknesses of conventional laboratory methods as well as sensing approaches. Furthermore, we emphasise their complementary roles in soil health assessment, as highlighted in Sections 10 and 11.

3. Demonstrate mechanistic integration showing how sensing technologies specifically enable

and enhance ecological soil health assessment in ways that traditional methods cannot, rather than presenting disconnected parallel concepts.

**Authors:** We appreciate the comment. While our intention was not to present sensing and ecological assessment as disconnected concepts, we recognise the need to demonstrate their mechanistic integration more clearly. Accordingly, in the revisions to Sections 9 and 10 (and the revised Figure 2), we now explicitly emphasise the connections between sensor capabilities and the ecological processes that define soil health, and we provide illustrative examples. We further highlight how conventional laboratory methods cannot effectively access these mechanistic pathways due to factors such as extensive sample preparation, potential alteration of natural equilibria, time lags between sampling and analysis, and high costs. In contrast, sensing technologies overcome many of these limitations by enabling high-resolution, timely, and more measurements that could capture dynamic ecological processes in situ. This makes sensing not simply a convenient alternative, but a fundamentally necessary approach for assessing soil health as an emergent property of ecosystems rather than as a collection of isolated soil attributes.

4. Provide a realistic implementation assessment including comprehensive discussion of research and development still required, standardization needs, economic barriers, and validation requirements for operational deployment across diverse soil-landscape conditions.

**Authors:** In the revised Section 11, we have included a subsection titled ' Advantages and limitations of sensing for soil health assessments' and 'Recommendations and research needs,' which comprehensively discuss the practical challenges and requirements for deploying soil sensing technologies in operational contexts. These sections address several key barriers highlighted by the editor, including outstanding research and development needs, standardisation requirements, economic and infrastructural constraints, and the necessity for robust validation across diverse soil-landscape conditions. Additionally, we discuss further considerations such as the transferability of empirical models, capacity building, and the need for ongoing collaboration to enable broad and equitable adoption.

Please thoroughly address these comments in addition to both reviewer comments.

Kind regards,

Jonathan Maynard

SOIL, Technical Editor

Specific Comments:

1. Lns 275-278. A related example of this is the land capability (LCC) and land suitablity (FAO GAEZ) assessment frameworks.

**Authors:** We thank the editor for pointing these out. We have revised the manuscript with these references.

2. Lns 288-289. In ecosystem management there are often intrinsic trade-offs between ecosystem services. A focus on ecosystem services tied to human values doesn't preclude incorporating an ecological perspective.

**Authors:** We thank the editor for the comment. We have revised Section 9 of the manuscript to clarify the balance between keeping soil health assessment in line with a scientific, value-neutral ecological perspective while remaining relevant to ecosystem services in practical management.

3. Lns 319-320. In most cases sensor-generated data are dependent upon conventional laboratory data to build calibrations and make predictions. Thus, the errors in the lab data will propagate in the sensor-based property predictions.

**Authors:** We agree that errors from the laboratory measurement do propagate to sensor estimates. We have restructured and revised the text to address point.

4. Lns 329-333. True, but all of this is dependent on sufficient data from conventional methods to calibrate sensor systems. For MIR and vis-NIR this is a significant initial investment. These sensor system are not operational out of the box.

**Authors:** We thank the editor for the comments. We agree that sensing measurements require conventional analyses for calibration. We did not intend that the sensing-based soil health assessment replace the conventional analysis. We have updated the manuscript to clarify this point.

5. Section 12. It is important to state that in most cases soil sensing data is not independent of conventional laboratory data. You need to first understand the properties, processes, and states of a system (determined from conventional methods) and its related sensor data to calibrate and model the desired property or class.

**Authors:** We thank the editor for the comments. We did not intend to indicate that sensing-based soil health assessment is independent of conventional measurement. We have revised the manuscript to clarify the point.

6. Figure 4. This is a central figure and should be supported by cited literature. Could include in a supplementary list or table.

**Authors:** Figure 4 is now Table 2, as this was requested by SOIL's editorial office. Table 2 was revised and now includes references.

7. Lns 357-359. Both vis-NIR and MIR require calibration, with vis-nir requiring sensor specfic calibration, while MIR is less susceptible to cross-instrument bias.

**Authors:** Thank you. We have clarified this in the revision.

8. Lns 375-377. Please provide more specifics here and in other sections reviewing the literature. What are current limitation with available sensing technologies for estimating biolgoical properties? How well has spectra been modeled with ML approaches to estimate biological indicators?

**Authors:** We have revised the manuscript to include more specific details on the performance and limitations of the sensing approach for biological properties.

9. Lns 385-386. What about TDR, FDF, capacitance sensors, Amoozemeter? Aren't these also considered sensor data?

**Authors:** We thank the editor for highlighting these additional sensors. Our updated Table 2 is not intended to be exhaustive; we acknowledge that there are many other valuable sensor technologies available. In selecting sensors for inclusion, we focused on mostly new technologies we thought most appropriate for soil health assessments. We do not mean to exclude TDR, FDF, or capacitance sensors. They are indeed useful and affordable solutions, primarily measuring soil moisture and electrical conductivity. We recognise their contribution to soil monitoring. However, a comprehensive review of all sensor types is beyond the scope of our work, and there are already at least three papers that focus on soil sensing reviews, which we cite in our manuscript. Note that the Amoozemeter functions as a manual or semi-automated apparatus rather than a sensing instrument.

10. Section 12.2. I agree that this approach holds promise, but to implement you need to adequately characterize the reference conditions or states (e.g, healthy, moderatly degraded, degraded, etc). This approach requires some set of categorical reference classes.
**Authors:** We agree that accurately characterising reference conditions is essential for effective implementation of this approach. In our revision, we clarify that we do not propose to replace established methods. Instead, conventional approaches can serve to strengthen and complement our proposed sensing-based framework, particularly in the initial definition and calibration of reference conditions. Once robust relationships are established between sensing signals and soil health states, our framework offers superior measurement efficiency and addresses data scarcity in ecosystem assessment and monitoring. As outlined in the manuscript, this sensing-based socio-ecological approach enables a more holistic, integrative, and practical assessment of soil health, moving beyond traditional reliance on isolated soil properties primarily driven by human needs. We believe this shift represents a necessary evolution for soil health assessment, which has changed little over the past decades.

11. On lines 433-434 your statement that ”this methodology is now sufficiently advanced to be implemented, offering a transformative tool for ecological soil health assessment” is not adequately supported by the evidence presented. The manuscript itself acknowledges critical limitations that contradict this claim:

- "Some soil properties remain difficult to measure with sensing, e.g., infiltration and hydraulic conductivity, and research and development is needed" (lines 385-386)
- "Standardised protocols for their use in soil health assessments are still underdeveloped" (lines 351-352)
- "No sensors are yet available for measuring soil fauna, such as earthworms or arthropods" (lines 378-379)
- Emerging technologies like microfluidics are "still in early stages of development" (lines 384-385)

These acknowledged limitations directly contradict claims of sufficient technological advancement for operational deployment.

**Authors:** We thank the editor for this thoughtful observation and acknowledge the critical limitations outlined in the manuscript. However, we maintain that these limitations do not preclude the implementation of our proposed framework. Most sensing technologies discussed are commercially available and have demonstrated successful applications in soil assessment over many years. These technologies have not yet been entirely leveraged to address the evolving challenges in soil health assessment. Importantly, the development and operationalisation of new soil health frameworks is inherently iterative, advancing through ongoing application, feedback, and refinement. While it is true that specific soil properties (such as infiltration, hydraulic conductivity, and soil fauna) remain challenging for current sensors, robust capabilities exist for measuring many key chemical, physical, and biological indicators that are central to widely adopted soil health frameworks. Our proposed methodology is not intended to replace conventional methods with sensing technologies; instead, we propose that these conventional methods will augment and supplement our proposed approach. Conventional approaches remain essential for indicators not yet accessible to sensors, and ongoing research is steadily expanding sensor capabilities for more rapid and affordable assessments. The manuscript has been revised to more accurately reflect the maturity and integration of available technologies, while recognising current gaps and areas for future innovation.

12. Figs 2 and 3 should be combined and expanded, providing examples to illustrate these connections. In its current form it is too general.

**Authors:** We have re-drawn Figure 2 and Figure 3 to address the editor's comments. We have also included a more detailed protocol (Figure 3 and accompanying text) as well as an application example.