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

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

Reviewer 2

There is lots of good information in this manuscript and it is generally well written. The biggest problem with this manuscript is that feels like it is two different papers. One idea is a review of the current lab-based assessment of soil health vs the proximal sensing of soil health. Both approaches have advantages and disadvantages, but they are both assessment framework neutral. This feels really valuable especially the discussion of how multiple sensors can be used. The other paper is about the author's suggestion for a more inclusive ecologically based soil health assessment approach. This second idea is underdeveloped and not directly related to the first idea. They provide a conceptual figure, but no actual guidance for how to do this other than "By directly measuring and monitoring soil properties linked to processes and functions." The sensor methods don't necessarily provide more direct measurements, they just make it possible to do a lot more measurements in space in time. My recommendation would be to remove the bulk of the discussion of soil health frameworks including the idea for a new framework and do a more coherent review of the measurements. For example, what are the citations that Vis-NIR or MIR can directly measure labile carbon and nitrogen or nitrogen mineralization? Finally, the paper delineates all the challenges of using the lab measurements and not any of the advantages, and then all the advantages of using sensors, but none of the challenges. A more balanced review is in order.

Authors: We thank the referee for taking the time to read our paper and for their conclusion that the paper provides good information and is generally well written. In our understanding, the reviewer has six primary comments and a recommendation. We address those next:

- Two papers rather than one. We respectfully disagree that this represents 'two different papers.' Our manuscript identifies the limitations of current soil health assessments and proposes a way forward. We note that the assessment is often an isolated activity in the existing literature, with no clear links to societal applications. Linking the two is an essential element of our paper. Our proposed solution is a framework that enhances the ecological perspective, with soil sensing as the core enabling technology. Both components are essential to improve soil health assessments in the real world, and in our manuscript, they are complementary rather than separate ideas.

- We acknowledge that the ecological framing could benefit from additional development. We designed it as a conceptual framework that is adaptable and scalable to different contexts and ecosystems. We will provide text to illustrate how practitioners, politicians, and regulators might use our framework.

- Some sensors can provide direct measurements—for example, electrochemical systems for measuring soil pH and available nutrients. Some sensing systems can also measure multiple soil properties integratively, for example, pXRF, LIBS, and vis-NIR spectroscopy. We cited publications that demonstrate such sensing (p. 18, lines 411–418 in the original submitted ms). Of course, as the referee states, sensing also enables the acquisition of many more measurements, but that is not all they do. We will revise Section 12.2 to clarify these points.

- We have included the citation for vis–NIR and MIR integrative measurement of labile carbon and nitrogen mineralisation in line 411 on p18, Fystro (2002); Russell et al. (2002).

- We agree that the discussion can be improved. While laboratory methods are well-established as the current standard, we focused on highlighting the advantages of sensing, which are less well-known. We will add a discussion on the challenges of soil sensing to balance the discussion. This is indeed a key point of the paper. Introducing sensing techniques that can provide extensive data over larger areas implies a paradigm shift compared to the cumbersome laboratory techniques that have been applied until now. This way, soil health can become a truly operational item in the political environmental debate.

- As we state above, we believe that describing techniques on the one hand and discussing their applications in future environmental policy and management is the key element of our paper. Specific reviews on sensing technologies already exist (which we have cited in the manuscript, e.g., Viscarra Rossel et al. (2011); Silvero et al. (2023)), and our goal here is to discuss how these technologies can be leveraged to advance soil health assessment with a new ecological perspective: linking science with society.

L18-24. This paragraph is problematic. It starts by talking about soil health. Then it switches to the connection between soil and human health. However, it doesn't make the connection between soil health (as generally discussed) and human health. There are soil contamination issues with toxins and pathogens, but that is not typically what is measured in any soil health assessment. It's fine to discuss all the functions of soils, but don't conflate soil health assessment with soil assessment. None of the later discussion talks about pathogens or toxins, so either take this out or explain more concretely how soil health is related to human health.
Authors: Thank you for the comment. This paragraph aims to establish the broader importance of soil (including the effect on human health) before narrowing to soil health concepts in subsequent sections. We will revise this paragraph to better distinguish between the broad importance of soil and the specific focus on soil health assessment that follows in the manuscript. We will more clearly distinguish between the two ways in which the concept of soil health is used. It is used for communication purposes: the scientist investigates the soil as a medical doctor investigates his patients. Both use indicators. This helps explain the concept to the public. At the same time, human health can be affected by soil pollutants, and focusing on indicators and thresholds of pollutants represents another focus.

L28 Similarly, this paragraph and the next one are about soil degradation, but the authors state without any citations that soil health is central to soil degradation. Are they just the converse of each other or is soil degradation a subset of soil health or vice versa. Please explain the relationship between soil health and degradation.
Authors: Thank you for the comment. We will add citations to clarify the relationship between soil degradation and soil health (Food and Agriculture Organization of the United

Nations, 2025; Kraamwinkel et al., 2021). Soil degradation is associated with a decline in soil health, indicating a serious decline that can be quantified by specific indicators and corresponding thresholds. This way, the dramatic term 'degradation' becomes much clearer and transparent.

L42-43 What are "the broader, multifaceted dimensions of soil health?" Does policies in this sentence refer to the previous sentence or is this just policies in general? Is the problem that they only focus on agricultural land or only certain functions. Either add more context or take this sentence out.

Authors: Thank you for pointing out this sentence needs clarification. By 'broader, multifaceted dimensions of soil health' we mean all the ecological functions of soil, including biodiversity support, nutrient cycling, pest regulation, and habitat provision, across diverse ecosystems. Soil health affects all of them. The 'policies' mentioned in lines 42–43 refer to soil health policies we mentioned in the paragraph in general. Our point is that current policies primarily emphasise specific soil functions, such as carbon sequestration and water quality, within agricultural settings, rather than addressing the full scope of soil health across different land uses. We will revise this sentence to provide clearer context and eliminate the ambiguity.

L48-49 What are "ecological needs of ecosystems?"

Authors: We'll clarify what we meant by it in revision. We meant intrinsic ecological functions that ecosystems require (the array of biological, geochemical and physical processes that occur within an ecosystem, including nutrient cycling, habitat provision, and biodiversity support...) for self-regulating, self-sustaining, and recovering from disturbances, that are independent of human management goals.

Sections 3-4 have lots of useful information, but it isn't clear how switching to sensor based measurements addresses any of the difficulties associated with the current assessment frameworks described here.

Authors: Thank you again for acknowledging that our manuscript is useful. In our submitted manuscript, we outlined the difficulties of the current assessment framework and how sensing would help to overcome those, see p14–p15 lines 312–343 (original submitted manuscript). We will ensure that this is again emphasised in the revised manuscript.

L170 One attempt to do this was published in https://doi.org/10.1016/j.soisec.2023.100084
Authors: Thank you for alerting us to that research. We will use it in our discussion. We acknowledge that their method is both scalable and adaptable due to the accessibility and logistical ease of the minimum dataset measurement. However, it is primarily based on the North American context and may not fully align with the specific goals or needs of other settings.

Section 6. Why is this section only about the field measurements? Aren't all these decisions about where to sample and how to standardize across equipment/users just as relevant for for sensors. MIR is a lab-based technique, so it still relies on collecting samples and processing them. For decades people have been studying variability among types of penetrometers (e.g. FRITTON, D. D.2. A STANDARD FOR INTERPRETING SOIL PENETROMETER MEASUREMENTS. Soil Science 150(2):p 542-551, August 1990). Field respiration varies from day to day and diurnally.
Authors: Thank you for this comment. Section 6 addresses the limitations of current soil health measurements broadly, including field sampling considerations and laboratory measurement challenges that affect conventional soil health assessments. Our discussion of sampling strategies at the beginning of this section (lines 192–197) applies broadly to soil health assessment regardless of the analytical method used. Note that much experience has been gained with sampling for fertility management, which is widely applied worldwide. We agree that sampling considerations apply to both conventional and sensing approaches (such as MIR), and we did not intend to suggest otherwise. We will clarify the scope of this section in the revision and ensure our discussion of sensing approaches adequately addresses both their capabilities and limitations regarding instrument precision where relevant. Sensors are not without measurement variability. However, they are practical and cost-effective, allowing practitioners to make an order of magnitude more measurements within the same budget compared to the more conventional analytical methods (Viscarra Rossel et al., 2022). This

increased measurement capacity leads to better characterisation of soil variability and a reduction in the estimation variance of soil properties (Viscarra Rossel et al., 2022).

Section 7 – 9 . Once again, there is useful information in this section, but how is it relevant to the review of lab vs sensor methods?

Authors: We thank the referee again for noting the uselessness of our paper. Section 7 identifies the challenges associated with current interpretations of soil health indicators, and Section 8 addresses the challenges of integrating these indicators. They are directly relevant to our paper because they highlight the limitations of current soil health assessments, which are essential and lead well to the proposed sensing-based soil health assessment framework. We structured the paper to first comprehensively identify the challenges across all components of soil health assessment before proposing improvements. Without discussing these current assessment limitations, the later sections on sensing approaches cannot be properly contextualised. The sensing methods we propose are specifically designed to address the challenges outlined in Sections 7 and 8. Section 9 follows and relates to our proposal that soil health assessments must have a more balanced ecological perspective.

L314-315 It is confusing whether the authors are talking about soil sensing or proximal soil sensing which some of the co-authors have been instrumental in defining (e.g. "the use of field-based sensors to obtain signals from the soil when the sensor's detector is in contact with or close to (within 2 m) the soil" Viscarra Rossel et al 2011). The title of the manuscript suggests proximal soil sensing, but then this sentence and the last paragraph of section 11 suggests that sensing can be in the laboratory too. For example, there is a much more robust history of using MIR in the lab than the field, so it would be really valuable to highlight the promising data from the field applications and for which measurements it seems to work as well as in the field as in the lab. A full discussion about the tradeoffs in data quality and cost/sample size even within the world of soil sensors would be extremely valuable and seems appropriate for a review paper.

Authors: Thank you for highlighting the confusion regarding our use of 'soil sensing' versus 'proximal soil sensing. We acknowledge that our manuscript discusses soil sensing in a broad sense, encompassing both proximal (field-based) and laboratory-based approaches. To address this, we will: (i) clarify terminology throughout the manuscript to distinguish between proximal and laboratory-based soil sensing, ensuring consistency and precision, (ii) revise the title to reflect the broader scope of the paper accurately, (iii) expand the discussion to differentiate the strengths, limitations, and applications of field (proximal) versus laboratory-based sensing methods, with particular attention to MIR spectroscopy and (iv) enhance our discussion on tradeoffs and limitations as suggested.

L329 This is more of the most valuable components of sensor based methods. Many of the frameworks that the authors describe need texture, but if that can be measured in the field, that is a huge benefit.
Authors: Soil vis–NIR can be used to measure soil texture in situ (e.g. Zhang et al. (2017)) and we acknowledge that in-field measurement requires careful accounting of the influence of moisture. Several methods can mitigate the effects of moisture on spectra Ji et al. (2015); Wang et al. (2016).

L348-349. One of the criteria is practicality/affordability. The authors should be more explicit that using proximal sensing would be a very different approach to soil health sampling. Half of the rows of affordable in figure 4 suggest that the measurements aren't affordable. Is it just a question of the cost of technology coming down or will these always just be for research and not widely used? The traditional lab based techniques permit anyone to collect and submit a sample while the lab has the expensive equipment. There are efforts to try to make soil health sampling very inexpensive for small holder farmers to do themselves (e.g. https://doi.org/10.1016/j.geoderma.2020.114539). The proximal sensing approach would require there to be companies that had the expertise to do the field sampling got hired to do the sampling and analysis, but do is require such specialized equipment and expertise that it wouldn't be possible for the technology to be widely available.
Authors: We thank the reviewer for commenting on the practicality and affordability of sensing for soil health assessment. We agree that this represents a shift from traditional laboratory-based methods and will make the distinction more explicit in the revised

manuscript. The rationale for employing sensing is that it enables the collection of a much larger number of measurements across space and time at a lower cost *per sample* than conventional laboratory analysis (e.g. (Li et al., 2022)). While traditional lab techniques often involve expensive and specialised equipment, complex procedures, and significant labour costs, sensors are typically simpler to operate, increasingly portable, and capable of collecting data rapidly and sometimes directly in the field. We acknowledge the accessibility concern, particularly for smallholder farmers and resource-limited regions. However, we posit that recent and ongoing developments in sensing are making these tools more affordable, easier to use, and widely available. Some sensors also offer multi-property measurements, further increasing their cost-effectiveness. We believe that, with continued innovation and decreasing hardware costs, sensing technologies will increasingly support soil health monitoring efforts in both developed and developing contexts. As suggested by Referee 1, we propose expanding the discussion to include consideration of how these technologies could benefit smallholder farmers, particularly in low-resource settings. Thank you for the citation to support this point. Regarding Figure 4, we apologise for any confusion about the affordability indicators. Eleven of twelve sensors are marked as 'affordable' (indicated by stars), with black stars indicating higher affordability than grey stars. Only microfluidic devices are currently deemed unaffordable due to their early stage of development. We will clarify this in the figure description in our revision.

Section 12. It would be really valuable if the review could discuss all the sensors/indicators in Figure 4. That would be the most novel and valuable part of the review and most useful to soil health practitioners. It would be especially valuable if there could be a comparison of the methods that do similar indicators. For example, Vis-NIR and MIR look identical in the table, but there are advantages and disadvantages to the two approaches. It would also be valuable if there was some discussion about how "good" these measurements are. For example, there has been way more work on trying to predict SOC than nitrogen mineralization.

Authors: Thank you for this suggestion; however, our focus here is not on reviewing and contrasting sensing technologies. There are various other reviews already in the literature that do this. We cited all of them (e.g., Soriano-Disla et al. (2014); Kuang et al. (2012); Viscarra Rossel et al. (2011); Silvero et al. (2023); Adamchuk and Rossel (2010)). Our objective here is to propose an ecologically centred framework for soil health assessments that has sensing at its core, presenting a link with environmental policy and society at large.

Figure 4. It is surprising to see infrared CO2 gas analyser in here. Soil respiration varies so much based on field conditions, it doesn't seem to fit with the other methods. Most of the current frameworks that do a measurement of respiration do a lab-based approach under standardized conditions. The difference between the green and the yellow is unclear. What does a direct measurement mean in this context? While the spectral techniques for SOC are based on the fact that different organic functional groups respond at particular wavelengths, the measurements is based on complicated algorithms and calibrations. This seems much less direct than combusting a sample and measuring the CO2. Similarly, the camera based techniques for structural stability really are directly measuring stability.

Authors: We appreciate the reviewer's comment and we will clarify these details in the revision.

- We included an infrared CO_2 gas analyser for soil respiration measurement, as it is the standard method for measuring soil respiration in both the lab and the field.
- 'Direct measurement' means the measurement of the soil property is made directly from the physical or chemical reaction between the sensor and the soil properties of interest. 'Indirect measurement' means the measurement is made based on the relationship between soil properties that can be directly measured by the sensor and the soil properties of interest. We will ensure that these are emphasised in the revision.
- Soil spectroscopy is a well-established soil analytical method, and so are the multivariate statistics used to extract information from the spectra. Soil spectra can cost-effectively estimate SOC. The approach is indirect, but physically based, as it relates to the soil's chemical composition. Compared to the conventional combustion method, one can measure orders of magnitude more samples at a significantly lower per-unit cost (noting also that a MIR spectrometer can cost less than one-third the

price of a C-combustion analyser, which also requires more sample handling and maintenance than the spectrometer).

- We agree that the camera-based techniques for structural stability directly measure stability. We will update this in the manuscript.

L404-405 I don't understand this sentence. Section 12 is all about the ways in which sensing is better at measuring the same indicators. It's not about new indicators. How does sensing changing the "selection of indicators."

Authors: Thank you for pointing out this unclear sentence. We will clarify this in the revision. Section 12 moves beyond measuring existing indicators. Specifically, what we meant by "Sensor signals provide a comprehensive range of quantitative soil information, minimising human bias in the indicator selection" is that the soil sensing signal can serve as an integrative indicator itself, incorporating multiple soil properties simultaneously without requiring pre-selection of specific properties. This reduces subjectivity in indicator selection compared to conventional methods.

L431-434 There was nothing in section 12 about integrating lab measurements and field measurements. This would be a valuable contribution to discuss which measurements are still hard to do with sensing and should be done in the lab.

Authors: We thank the reviewer for raising this point. We will include a brief discussion on the use of sensing in conjunction with conventional laboratory analysis as a current practical approach for assessments.

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