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

Below, we provide our responses in blue text

Dear Authors, Thank you for submitting your revised manuscript on soil health assessment and proximal sensing technologies. This ambitious work addresses critical gaps in conceptualizing and operationalizing soil health assessments, and I appreciate your efforts to address the reviewers' concerns. While you have resolved many of the initial issues, several areas still require development. The revised technical sections (Sections 10 and 11) are well done, with good balance between specificity and examples. Section 11.4 particularly stands out for its detail and should serve as a model for other sections. The abstract and early sections need sharper definitions of key terms and clearer articulation of how your framework differs from and improves upon existing approaches. Additionally, the frameworks presented in Figures 2 and 3 must be internally consistent with each other and with the text, while remaining practically implementable by your intended audience. The manuscript also needs stronger integration between the soil health review (Sections 4-8), your proposed framework (Section 9), and the sensing technologies (Sections 10-11). These components currently read somewhat independently rather than building toward a cohesive argument that demonstrates how the review informs your framework and how the sensing technologies enable its implementation.

Addressing these issues will significantly strengthen the manuscript and its contribution to the field.

Authors: Thank you. Below, we address your additional comments.

Major Comments

1. Structural and Organizational Issues

While there have been some improvements to connect and demonstrate how sensing technologies enable and enhance your proposed soil health framework, the ecological framework section (Section 9) and sensing technologies sections (Sections 10-12) are not

sufficiently integrated with the previous sections. The readability and coherence of the manuscript would be significantly improved by reorganizing several of the sections. The current progression from critiquing existing approaches (Sections 2-8), to proposing your framework (Section 9), to discussing sensing technologies (Sections 10-11) feels disjointed and may create confusion for readers. Most problematically, given that the title emphasizes the 'pivotal role of proximal sensing,' the fact that sensing technologies are not substantively addressed until Section 10 is confusing. Readers expect sensing to be a central organizing theme throughout the manuscript, not an add-on discussion in the final sections.

My recommendation is to reorganize several sections of the manuscript. Although each section is generally well presented, the central premise of the paper does not become clear until halfway through. I recommend that you present your integrative framework much earlier (perhaps after Section 3 or 4), then systematically demonstrate how this framework, with sensing as a core enabling technology, addresses specific limitations of existing approaches identified in your review. This would create a more coherent narrative and better align the structure with your stated emphasis on sensing's pivotal role. Reference to sensing technologies should be woven throughout the manuscript as the methodological foundation of your proposed framework.

Below is a suggested reorganization that would not require significant editorial changes.

• Sections 1-4 stay the same, no major changes, establishes the problem definition

• Section 5 (Current Section 9). Presenting your solution early creates an organizing structure for the remainder of the manuscript. Instead of critiquing existing approaches for many pages before revealing your framework, readers understand your proposed solution upfront and can evaluate subsequent discussions in context.

• Sections 6: Current Limitations of Soil Health Assessment Frameworks (Current Sections 5-8), no major changes, provides detailed analysis of current approaches, need to cross reference to your proposed framework:

- 6.1 Indicator Selection Challenges (Current Section 5)
- 6.2 Measurement and Interpretation Challenges (Current Section 6 and 7).

- 6.3 Integration into Indices (Current Section 8).

• Section 7: Sensing Technologies as Enabling Tools for Soil Health (Current Sections10-11), no major changes. Subsections follow existing sequence of sections. At the beginning of this section, you should provide a brief overview connecting sensing capabilities to framework requirements, emphasizing the need for methods that are (1) rapid and cost-effective, (2) capable of capturing spatial and temporal heterogeneity, (3) applicable across diverse ecosystems, and (4) scalable from field to landscape levels; and that while traditional laboratory methods provide high accuracy and precision, they cannot alone meet these requirements at the scales demanded by contemporary soil health challenges.

• Section 8: Conclusions (Current Section 12). Provides a synthesis and path forward If you choose to keep your current organization then you'll need to improve the connections between your review of soil health assessment frameworks (Sections 4-8) and your proposed framework (Section 9) and sensing technologies (Sections 10-11).

Authors: We have revised the paper as follows. (1) We added a brief new subsection in the introduction to describe our idea, the purpose of the manuscript and as a guide for readers to understand how we structured the manuscript. Second, we reduced the 12 sections to six: 1. Introduction, 2. Soil health concepts and current practice, 3. An integrative framework for soil health assessments, 4. Sensing for characterising soil health, 5. Recommendations, research needs, and 6. Conclusions. The paper is not long, but we agree it appeared so, with 12 sections, and introducing the main ideas in section 9 was not sensible. We appreciate the suggestions above, but we prefer to maintain our current structure (with the proposed revisions, of course), as it aligns with our intended problem-definition—proposed-solution logic. We believe our revision now clearly articulates the paper's main premise right at the start, without compromising our original logic.

2. Conceptual Framework Development

The proposed framework (Figure 2, Section 9) still requires further development/clarification. Currently, it lacks clarity regarding how soil health should be evaluated relative to soil-specific potential, a fundamental consideration given that different soil types have inherently different

capacity ranges. This is crucial: the value of any soil indicator needs soil-specific context to interpret how healthy a given soil is. For example, the Alberta grassland you discuss (lines 332-334) illustrates this perfectly: if we define soil health as the condition of the soil referenced to its quality (the range of possible conditions for that soil type), then that grassland soil is likely at the higher range of functional conditions for that soil type, as demonstrated by its ability to support native vegetation. You must distinguish more clearly between: (1) assessments of soil condition/health/potential, and (2) assessments of soil within specific interpretive management frameworks (e.g., Land Capability Classification, GAEZ). The Alberta grassland may never grow potatoes, but it's a very productive native grassland. It's important to separate the assessment of what the soil 'is' from assessments of what it can 'do' for specific human purposes.

Authors: Yes, soil-specific potential and the distinction between ecological condition and use-specific interpretation needed to be made more explicit in the framework section. In the revised manuscript, we have therefore added a short clarification stating that indicator values are interpreted in relation to the expected range of conditions for the soil type being evaluated (soil-specific potential), and that this ecological assessment of soil health is conceptually distinct from interpretive management frameworks that evaluate the suitability of a given soil state for particular uses (e.g. land capability and crop suitability). The Alberta grassland example is now used explicitly to illustrate that, while the soil may never support high-yield potato production, it can still be assessed as relatively healthy when judged against its soil-specific potential and its ability to sustain a productive native grassland ecosystem.

We have revised as follows: (1): '...In the proposed framework, soil health assessments interpret indicator values in relation to the expected range of conditions for the particular soil being evaluated, that is, its soil-specific potential. This means that the ecological condition of a soil is judged against what is inherently achievable for that soil, rather than against an agronomic optimum. In the southern Alberta grassland example, the same indicators that classify the soil as 'unhealthy' for intensive agriculture can indicate a relatively healthy soil when interpreted against the soil-specific potential of that grassland soil, as demonstrated by

its capacity to support native vegetation and associated ecosystem functions.' (2): 'This ecological assessment of soil health is distinct from interpretive management frameworks, such as land capability classifications or crop suitability assessments, which evaluate how a given soil state constrains or enables specific uses. In the southern Alberta grassland, for example, the soil may never be capable of supporting high-yield potato production, yet it can still be assessed as relatively healthy considering its soil-specific potential and its ability to sustain a productive native grassland ecosystem. Separating the assessment of what the soil is from assessments of what it can do for particular human purposes allows the same ecologically grounded soil health evaluation to support diverse management and policy decisions....'

Consequently, the revised Figure 2 still presents some conceptual confusion that undermines the clarity of your proposed framework. The expansion of the 'soil system' into both natural ecosystems and socio-cultural systems creates confusion about your main argument. If, as you state, soil health should be grounded in its intrinsic ecological functions, then the soil system should reside solely within the natural ecosystems box, with an arrow connecting it to socio-cultural systems to show how ecosystem services flow from ecological functions. Consider revising Figure 2 to: (1) place the soil system clearly within the natural ecosystems domain, (2) add an explicit component showing how soil health is referenced to soil-specific potential, and (3) more clearly delineate the boundary between ecological assessment and socio-economic interpretation. Additionally, while Figure 3 outlines the general workflow, it would be substantially more informative with a concrete hypothetical example. Consider adding example boxes next to each element that illustrate some of the practical considerations needed to implement this workflow.

Authors: We revised Figure 2 (Figure 3 in the revised ms) to clarify the relationships between natural ecosystems, socio-cultural systems, the soil system and soil health assessments. In the new version, the soil system is represented as a distinct box beneath the natural and socio-cultural, with arrows from both to indicate that soils function within and are influenced by both domains. Soil health assessment is then shown (like we did originally), as a separate, ecologically grounded step directly from the soil system. In the Figure caption, we indicate that assessments are made relative to soil-specific potential and are subsequently

interpreted within use-specific management frameworks. These changes preserve our intended message that soil is central to both ecological and socio-cultural systems, while more clearly delineating ecological assessment from socio-cultural interpretation. Please note that we disagree with the assertion that the soil system should be situated solely within the ecological domain. Soil is central to both domains, and we argue that **ecological principles** need to be applied when assessing soil health in either domain.

We agree that the workflow in Figure 3 (Figure 4 in the revised ms) is clearer when accompanied by a concrete example. We have revised it and now refer explicitly to the mine-site rehabilitation example in Section 3.3 (of the revised ms) as an illustration of each step in the sensing-enabled workflow and have updated the caption and Section 3.3 to make this connection explicit. The revised figure caption is: 'Figure 4. Sensing-enabled soil health assessments. The mine-site rehabilitation example in section 3.3 illustrates each step in the sensing-enabled soil health assessment for a specific application.' We also made this link more explicit by adding the following in Section 3.2 Implementing the sensor-based framework: 'The example of mine-site rehabilitation (Section 3.3) demonstrates how each step of the sensing-enabled assessment can be implemented in practice.'

Specific Comments Abstract: The abstract could be strengthened with a clearer, more upfront explanation of why sensing technology is central to your approach. I recommend framing this as a practical constraint, i.e., you need measurements that are fast, affordable, and work across different ecosystems and scales. Traditional laboratory work, while precise, simply cannot alone deliver data at the scales required for landscape-level soil health assessment. Therefore, the sensing technologies aren't just convenient, they're the only feasible approach for comprehensive soil health monitoring. This more explicit framing would help readers immediately grasp why your framework is built around sensing technologies rather than just conventional methods.

Authors: We have revised the abstract as follows:

'Soil underpins the functioning of all terrestrial ecosystems and human societies, yet its accelerating degradation demands urgent action. Sustainable soil management is essential to

prevent further degradation and achieve sustainable land use. Many countries and supranational organisations have embraced the concept of soil health and integrated it into policy, but critical gaps persist in how soil health is assessed and implemented in practice. Clear operational procedures are needed to consistently evaluate soil health, communicate transparently with policymakers and stakeholders, and ensure that management decisions respect both the ecological functioning of soils and the services they provide to society. Soil health is often framed either from an ecological perspective, emphasising soil processes and functions, or from a socio-economic perspective, emphasising ecosystem services and productivity. Treating these perspectives in isolation has led to policies and agronomic practices that prioritise short-term outputs while neglecting the ecological principles that sustain soil systems, especially in managed landscapes. Here, soil health is instead approached as a property of the soil system that is central to both natural and socio-cultural domains: assessments consistently apply ecological understanding of soil processes and functions, whether soils are in natural ecosystems or in intensively managed agroecosystems. Conventional soil analysis alone cannot provide the continuous, spatially explicit information needed for timely and effective soil health evaluation because it is slow, costly, and spatially limited. Modern technologies such as soil and remote sensing, statistical modelling, machine learning(ML), and artificial intelligence (AI) are therefore not merely useful additions but the only feasible means of generating rapid, affordable, precise, and scalable soil information across diverse ecosystems. Here, we review the conceptualisation of soil health, criteria for selecting indicators, current assessment frameworks, and the use of modern technologies to overcome operational constraints. Most published studies on soil health focus on agriculture, yet current environmental challenges demand a broader perspective that includes other ecosystems and land uses. We propose an integrative framework that explicitly links two complementary perspectives on the soil system: (1) its ecological integrity, captured by the physical, chemical and biological processes and functions that sustain it, and (2) the ecosystem services and societal benefits that arise when these functions operate within natural and managed landscapes. The framework integrates soil and remote sensing with advanced analytical approaches, such as statistical modelling, ML, and AI, enabling objective,

quantitative, reliable, rapid, cost-effective, and scalable soil health assessments. By consistently applying ecological principles to soils in both natural and socio-cultural contexts, and then interpreting the resulting assessments in terms of ecosystem services and societal goals, this sensing-enabled framework supports soil management and policy that advance both environmental stewardship and the UN Sustainable Development Goals (SDGs).'

Lns 8-10. How is the soil overlooked? Try to be more specific. There are lots of operational procedures for measuring soil health; what is needed are operational procedures that account for soil multifunctionality and the full spectrum of ecosystem services. Without this, policies will continue to prioritize narrow management objectives while overlooking the soil's broader ecological roles.

Authors: We have already addressed the editor's comment on our abstract.

Lns 16-24. Terms like 'socio-ecological perspective' and 'ecological integrity' need clearer definition in the abstract. Readers should understand these concepts without having to wait for explanations later in the manuscript. Consider presenting your framework more clearly as addressing two complementary perspectives: (1) the ecological integrity of soil ecosystems, and (2) the services they provide to society. Emphasize that soil health is quantified within the ecological domain based on soil processes and functions, which are then used to inform the interpretation of ecosystem services. Only by addressing both perspectives can we support policies that achieve both environmental protection and sustainable development goals. This dual framing should be explicit from the outset.

Authors: As above.

Lns 93-94. Your third objective states you will 'describe how soil sensing and other innovative technologies can support the proposed framework.' This objective would have even greater utility if the stated goal also included a pragmatic discussion/evaluation of the current challenges and future work needed to operationalize soil sensing and other technologies for soil health assessments, which you've done nicely in Section 11.4. The potential exists, but considerable work is still required, and acknowledging this explicitly in your objective would strengthen your argument.

Authors: We have updated the third objective to acknowledge the discussion of the challenges and future work. It now reads: ' Describe how soil sensing and other technologies can support the proposed framework and enhance soil health assessments, and critically evaluate the current challenges and future research needed to operationalise these technologies.'

Lns 104-106: Your distinction between soil health (current condition of a specific soil) and soil quality (expected range of values for a given soil type) is valuable and should be emphasized more throughout the manuscript. This distinction is key to resolving many of the conceptual ambiguities in the soil health literature.

Authors: We agree the distinction between soil health and soil quality is indeed conceptually important for resolving conceptual ambiguities. Therefore, the definition is clarified early in the 'Defining soil health' section, and the manuscript then builds on it. The arguments in the later sections no longer focus on the distinction between soil health and soil quality. Re-emphasising the conceptual distinction in these later sections may be redundant and distracting. No change was made.

Figure 1: What is the significance of the different colors in Figure 1? This should be explained in the figure caption.

Authors: The updated figure caption reads:'Note: Available sensors for soil health assessment and their capabilities. The soil health indicators shown are the most frequently used, as identified by Bünemann et al. (2018). (vis–NIR: Visible and near-infrared spectroscopy; mid-IR: Mid-infrared spectroscopy; LIBS: Laser-induced breakdown spectroscopy; XRF: X-ray fluorescence spectroscopy; AγA: Active gamma-ray attenuation), ER: electrical resistivity sensor; EMI: electromagnetic induction; TOM/TOC: total organic matter or total organic carbon; D: direct measurement highlighted with blue colour; I: indirect measurement based on correlation with directly measurable properties highlighted with pink colour; 'Moderately' indicates partial satisfaction to the criteria.'

Lns 147-152, Page 6: You make a valid point about focusing on ecosystem functions providing

an objective framework. However, focusing on ecosystem functions without referencing these values to the potential range of values for a given soil can also be misleading. The value of any ecosystem function indicator needs soil-specific context in order to interpret how healthy a given soil is. This point deserves more explicit treatment in your framework.

Authors: We thank the editor for the comment. Our intention in this paragraph is to emphasise that soil health should be grounded in ecological principles rather than solely in human-centred ecosystem services. We agree, however, that interpreting ecosystem function indicators requires soil-specific context and knowledge of the expected range of values for a given soil type. To avoid potential misunderstanding, we have added a clarifying phrase indicating that ecosystem functions must be evaluated within the natural range of conditions for the specific soil and ecosystem.

The revised paragraph now reads: 'However, equating soil health solely with its capacity to deliver services is inadequate, much like assessing human health purely by economic output or productivity. A more effective approach is to focus on the inherent state of the soil ecosystem and its ecological functions within the natural boundaries of the specific soil type and ecosystem. Ecosystem functions—representing the processes and structures within an ecosystem—provide an objective, value-neutral framework for assessing soil health, distinct from ecosystem services.'

Measurement and Sampling Lns 229-234: Consider starting Section 6 ('Measuring Soil Health Indicators') with a reference to the measurement accuracy/precision required for different indicator. Different properties exhibit: (1) different degrees of spatial and temporal variability, thus potentially requiring different sampling strategies, and (2) different degrees of measurement error. This context would help frame the subsequent discussion.

Authors: We revised the paragraph to highlight this point: 'Different indicators, locations, and assessment objectives require different sampling strategies to achieve the desired accuracy and precision, particularly for digital soil mapping (Brus and De Gruijter, 1997; Lawrence et al., 2020).' We agree that this context is important for framing the subsequent discussion; however, we prefer to start the paragraph with a broader comment regarding sampling for soil

health in general, before narrowing to indicator-specific accuracy and precision requirements.

Lns 233-234: When you mention 'frameworks like the one proposed by Lawrence et al. (2020) offer structured guidance for improving soil sampling. . . .,' be more specific about what type of structured guidance. Sampling strategies need to consider the spatial and temporal variability for a particular indicator, which can have a huge effect on how well it truly represents the sampling unit.

Authors: We have revised this paragraph to include references to the different sampling strategies required for different indicators, including the reference to Lawrence et al. (2020).

The paragraph now reads: 'Many soil health assessment frameworks provide only rudimentary soil sampling guidelines. For example, CASH (Table **??**) recommends combining samples from five to ten subsoil locations along a zig-zag transect (Moebius-Clune, 2016). Other frameworks suggest general strategies, such as random sampling, W-shaped walks, or circular transects (Stott, 2019), but these approaches often fail to adequately capture soil variability. In practice, robust sampling must be tailored to the specific purpose of the assessment and should account for the strength and nature of spatial variability in the soil health indicators being measured. Different indicators, locations, and assessment objectives require different sampling strategies to achieve the desired accuracy and precision, particularly for digital soil mapping (Brus and De Gruijter, 1997; Lawrence et al., 2020). Frameworks like the one proposed by Lawrence et al. (2020) offer structured guidance on selecting between design-based and model-based soil sampling, defining management goals, and determining appropriate sampling densities and layouts to improve soil sampling in soil health assessments.'

Lns 251-255: Your statement about 'growing demand for fine-resolution soil data across large spatial and temporal scales' highlights the need for high-throughput methods that can accommodate the large sample sizes required to characterize indices at fine spatial/temporal scales, e.g., soil sensing methods. However, it must also be acknowledged that although sensing methods offer higher throughput, they often have lower accuracy/precision per sample. This tradeoff should be addressed explicitly.

Authors: We thank the editor for noting this. In lines 587- 590 (previously revised manuscript), we acknowledged that although sensing methods have lower precision per sample, their higher throughput enables analysis of more samples, thereby providing a more informative overall measurement.

Ln 253: The statement 'The assessment of soil health by Reijneveld et al. (2024) could only be realized by applying innovative methods' needs more context. What type of innovative methods? Since soil sensing is a major theme of your manuscript, it should be more explicitly incorporated into these sections rather than being introduced abruptly later.
Authors: We thank the editor for pointing this out. We have clarified the 'innovative methods' in the sentence. The revised sentence now reads: 'The assessment of soil health by Reijneveld et al. (2024) could only be realised by applying innovative measurement methods, including modern analytical and sensing-based approaches (discussed further in section 10) to quantify heavy metals, biocides, and microbiological conditions in a rapid, precise, and cost-effective and scalable manner.'

Ln 293: Your discussion of threshold values is important, but the reference to the European Environment Agency defining threshold values is too vague. The EEA report actually highlights the complexity of setting threshold values and how this depends on management context (e.g., pH thresholds for different crops). This complexity deserves acknowledgment.
Authors: We have revised the text to acknowledge that the EPA emphasises the complexity and context-dependence of threshold setting regarding threshold definition.

The updated paragraph now reads: 'The European Environment Agency has already defined threshold values for key indicators (Agency, 2023). A recent review summarised four methods for establishing threshold or target values: (1) using fixed values from existing research or practical experience, (2) using values from reference sites, (3) situating indicator values within distributions for similar soils (stratified by soil type, land use, and climate), and (4) assessing relative changes in indicators over time (Matson et al., 2024). The relative-change approach, identified as the most promising, relies on representative chronosequence data, which

substantially increases sampling requirements. Quantitative research is limited, particularly for indicators linked to multiple soil functions, such as soil organic carbon storage, and for those with complex interactions. Importantly, the complexity of the setting is emphasised by EEA, as threshold-setting is inherently context-dependent, varying with soil function, land-use type, climate, and management objectives, and therefore requires substantial contextual data to be established reliably. Generating the breadth of data needed to support robust threshold development, therefore, depends on more efficient, scalable measurement approaches.'

Lns 300-302: Your statement 'Rapid and cost-effective methods for assessing soil health indicators are urgently needed to support the development of actionable thresholds' is a critical point. Consider moving this up and placing it immediately after your earlier statement that 'Threshold and target values for soil health indicators are critical for connecting indicator interpretation with management and policy (Bouma and Reijneveld, 2024).' This would better establish why sensing technologies are essential to your proposed framework.

Authors: We agree that positioning the statement after the discussion of thresholds and target values strengthens the connection between indicator interpretation and the technological limitations that sensing can address. We have moved the sentence up.

The paragraphs now reads: 'Threshold and target values for soil health indicators are critical for connecting indicator interpretation with management and policy (Bouma and Reijneveld, 2024). Target values represent achievable management goals, whereas thresholds identify critical thresholds for soil-function decline that necessitate intervention. Scientific understanding must inform indicator thresholds (Matson et al., 2024; Agency, 2023).Reijneveld et al. (2024) emphasises the importance of separating indicators and defining threshold values to distinguish between 'good' and 'not yet good enough', allowing research to focus on indicators that fall short. Developing robust and broadly applicable thresholds, however, requires rapid and cost-effective methods for assessing soil health indicators, particularly where large, representative datasets are needed across diverse soils and land uses.'

Lns 332-334: This where an important distinction needs to be made in terms of definitions. If we define soil health as the condition of the soil and that condition is referenced to the soil

quality or range of conditions, then the Alberta grassland soil is likely at the higher range of functional conditions for that soil, demonstrated by its ability to support native vegetation. Assessments of soil capability (e.g., LCC) or soil suitability (GAEZ), or any other interpretive framework will evaluate this soil, along with all other soils, relative to some specific reference system for a given management objective. It may never be able to grow potatoes but is a very productive native grassland. It's important to distinguish between assessments of soil condition/potential vs assessments of soil within a specific interpretative management framework. You are essentially getting at this point here but need to highlight that this confusion stems from a confusion in definitions.

Authors: We have revised as follows:

'For instance, in a southern Alberta grassland, Janzen et al. (2021) showed that agronomic criteria deemed the soil 'unhealthy' due to low organic matter content, alkaline pH, and thin topsoil, whereas an aesthetic landscape evaluation rated it as 'healthy'. Both perspectives used similar indicators but interpreted them through different, use-specific lenses, implying soil health is defined from a perspective to serve a particular human desired purpose, assessing soil for the suitability or capacity of soil to achieve specific management objectives, rather than the soil's condition relative to its own potential to support the ecological functioning of the native ecosystem. This human-centric framing leads to the conflation of soil health with use-specific definitions and interpretive frameworks, thereby obscuring the objective assessment of its ecological value. What is needed is an objective, ecologically grounded definition of soil health, distinct from suitability for particular land uses, so that consistent and operational procedures for assessing soil condition can be established.'

Lns 342-343: The expansion of the soil system into both natural ecosystems and socio-cultural systems in Fig. 2 confuses your point made in the previous paragraph. If soil health is grounded in its intrinsic ecological functions, then it should solely reside with the natural ecosystems box, with an arrow connecting it to socio-cultural systems.

Authors: We have revised Fig. 2 (original ms) to place the soil system in a separate box below the natural ecosystem and the socio-cultural system, with arrows indicating the soil's

role in both domains. We have addressed the premise of this comment above. Our framework aims to present a balanced view of the natural and socio-cultural domains—the soil itself remains central to both. We revised the figure caption as follows: 'A conceptual framework showing the soil system between natural ecosystem and socio-cultural domains, reflecting soil's central role in sustaining ecological functions and supporting human needs. Soil health assessment is grounded in ecological understanding of soil properties, processes and functions, and its outcomes are interpreted within environmental and socio-cultural contexts.'

Lns 373-374: Laboratory analysis is still the gold standard for soil characterization. Sensor data is dependent upon lab data for calibration and is generally less precise. Sensor data serves as a compliment to conventional lab data but is not a replacement. Consider revising to something like: 'Sensor data often provide high-resolution, continuous, multi-property representation of soil conditions, providing greater temporal and spatial ecological relevance than infrequent measurements from conventional laboratory procedures.'

Authors: This sentence has been revised as follows: 'Sensor data often provide precise, high-resolution, continuous, multi-property representation of soil conditions, providing greater temporal and spatial ecological relevance than infrequent and few measurements from conventional laboratory procedure.'

Ln 392: Awkward phrasing, consider: 'meaningful soil indicators can be extracted from sensor data'.

Authors: The sentence now reads: '...meaningful soil indicators can be extracted from sensor data, positioning sensing as a transformative tool for a next-generation of soil health assessment and monitoring.'

Lns 408-409: Your statement 'might be benchmarked against reference sites, distribution-based thresholds, or temporal trends.' is an important detail missing from the presentation/discussion of your soil health framework (Fig. 2).

Authors: We agree that benchmarks and thresholds are essential for interpreting soil health indicators, but Figure 2 (original submitted ms) itself is a high-level conceptual model on the

relationship of soil health and soil system to the natural ecosystem and socio-cultural domains. It is not intended to depict methodology or workflows. Figure 3 (original ms) does show implementation steps, including interpretation in step 5, where 'benchmark against reference sites, distribution-based thresholds, or temporal trends' fits. Our framework is method-agnostic and accommodates various interpretation strategies, as reviewed in Section 7 (many existing approaches for indicator interpretation, e.g., scoring functions, reference conditions, distribution-based comparisons, temporal trajectories, and model-based methods), as different ecosystems, management goals, and data availability will determine the most appropriate interpretation approach.

We added the following sentence to clarify: '...might be benchmarked against reference sites, distribution-based thresholds, or temporal trends. Soil sensing offers advantages for implementing these approaches; for example, spectroscopy can efficiently characterise mineral-organic baseline conditions across diverse undisturbed sites at a lower cost than conventional analytical measurements; distribution-based thresholds can be established from large-scale sensor datasets that capture the natural variability of soil properties across soil types, climate zones, and land uses, and temporal trend analysis is enabled by rapid, cost-effective repeated measurements at frequencies that reveal seasonal dynamics and long-term changes.'

Ln 573: 'Sensing provides important advantages for soil health assessment.' , consider adding: 'that complement conventional methods.'

Authors: We have revised the sentence, and it now reads: 'Sensing provides important advantages for soil health assessment by extending and complementing what conventional laboratory methods can offer.'

Table 3: Under advantages 1. 'Fewer errors and disturbances': Sensors don't always have fewer errors, but rather different error sources (calibration drift, interference, environmental effects). Consider changing to: 'Reduced sampling disturbance'

2. 'Improved precision (more granular)' change to 'improved data precision (more granular)' Consider adding additional 'Limitations' and 'Solutions': Additional 'Limitations':

- Calibration drift and maintenance needs
- Environmental interference effects
- Limited to easily measurable properties
- Data management complexity
- Lower analytical precision than labs for specific analyses

Additional 'Solutions':

- Develop hybrid sensor-lab protocols
- Create open data standards
- Establish sensor certification programs
- Build decision support tools

Authors: We have incorporated some of the edits, additional limitations and solutions suggested; however, not all. We did not include 'Calibration drift and maintenance' because these are common to all instruments used to measure soil properties. We also did not include 'Limited to easily measurable properties' because, as discussed in Sections 10 and 11 of the manuscript, one of the key advantages of sensing is its ability to estimate properties that are difficult, labour-intensive, or impractical to measure conventionally. While some properties remain challenging for sensors, characterising sensing as limited to 'easily measurable' traits is misleading and does not reflect the discussion in the manuscript. We used 'Limited direct measurement of some properties' instead.

Revision to 'Advantages and limitations of soil sensing for soil health assessments' section: 'Sensor measurements are also affected by environmental interference, including soil moisture, temperature, electrical conductivity, and surface conditions (Adamchuk and Viscarra Rossel, 2010; Fan et al., 2022), which needs to be accounted for through experimental design or compensation algorithms (Ji et al., 2015).' 'Furthermore, implementing a sensing approach

for soil monitoring requires robust data processing and storage capacity, reliable connectivity, and sufficient computational power to handle and process large datasets (Fan et al., 2022).' Revisions to 'Recommendations, research needs' section: Sentence added to the first paragraph in this section: 'Furthermore, sensor certification programs should be developed to verify instrument performance and measurement precision against standardised protocols, analogous to accreditation systems for conventional laboratories.' Sentence added to the third paragraph in this section: 'Realising the full potential of these libraries requires establishing open data standards and interoperability protocols that enable seamless integration of sensor data from different instruments, soil types and geographical regions.' Sentences added to the soil sensor database paragraph: 'To maximise the value of both approaches, we should also develop and test hybrid sensor-laboratory protocols that optimise the strengths of both approaches, by leveraging sensing for high-density spatial-temporal coverage with complementary targeted conventional laboratory analyses for calibration and validation where needed.' Sentence added to after 'friendly platform diverse stakeholder': 'Such as the development of decision support tools that translate complex multi-sensor data into intuitive visualisations, interpretation guidance, and management options recommendations for stakeholders' specific contexts and objectives.'

Sections 10 and 11. The revised text on sensing capabilities is much improved and appropriately balanced. The mine site rehabilitation example provides helpful concrete illustration of framework application. The discussion of multi-sensor fusion has been revised appropriately and now better reflects both the potential and challenges of combining data from multiple sensors. The revised discussion of integrative sensing approaches is clearer and more compelling. Section 11.4 on recommendations and research needs is well done with good balance of specificity and examples to support the discussion. This level of concrete detail should serve as a model for earlier sections. Consider adding more concrete examples to illustrate abstract concepts. The Alberta grassland example is effective precisely because it makes conceptual issues tangible. More examples like this would substantially strengthen the manuscript. **Authors:** We appreciate the editor's positive assessment of the revisions.

In summary, your manuscript requires additional revisions addressing the following points:

- Reorganize/revise the manuscript to introduce your framework early, then use it to structure the critique of existing approaches and demonstrate how sensing enables implementation.
- Sharpen key definitions (especially soil health vs. soil quality) and specify how your framework operationally differs from existing approaches.
- Position sensing as central throughout the manuscript, explicitly framing it as a practical necessity for landscape-scale assessment rather than a late add-on.
- Further revise Figures 2 and 3 for internal consistency, conceptual clarity, and practical implementation with concrete examples.
- Replace abstract discussions with tangible examples and specific details throughout (following Section 11.4 example).

We appreciate the editor's detailed comments. We believe the revisions described above directly address these points while remaining consistent with the logic and intent of our manuscript.

References

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