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. How would practitioners actually select indicators using your approach? What specific decision rules or criteria distinguish your multi-criteria selection process from existing methods? 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.

**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).

**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.

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.

**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.

**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.

**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.

**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.

**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.

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

**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.

**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.

**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.

**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.

**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.

**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.

**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.

**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.

**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.

**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."

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

**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).

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

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

**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.

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).

Please thoroughly address these points in your revision and I am happy to provide additional clarification if needed.

Kind regards,

Jonathan Maynard

SOIL, Technical Editor