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OPINION

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A new theory for soil health

James A. Harris[1] | **Daniel L. Evans**[1] | **Sacha J. Mooney**[2]

[1]School of Water, Energy and Environment, Cranfield University, Bedfordshire, United Kingdom

[2]Division of Agricultural & Environmental Sciences, School of Biosciences, University of Nottingham, Nottinghamshire, United Kingdom

Correspondence
James A. Harris, School of Water, Energy and Environment, Cranfield University, Bedfordshire, United Kingdom.
Email: j.a.harris@cranfield.ac.uk

Abstract

The term "soil health" has captured the interest of government, and land managers, whilst the academic community has struggled to rationalise its use and wider benefit. It has proved a powerful tool in conveying best practice to a lay audience. However, the widespread adoption of the "metaphor" has resulted in calls for tools that facilitate the measurement of soil health, preferably quantitatively, and often as a single figure, for ease of use/communication and cost of monitoring. The insurmountable problem is that soil health is neither a readily quantifiable nor measurable object. Only organisms can have 'health', which manifests as characteristics of a living system—true of complex systems exhibiting "emergent" properties such as resilience in the face of perturbation. We pose the key question: is soil really a system capable of exhibiting "health", or any other property emerging from a complex, connected, self-regulating system? We argue that if you cannot detect emergent properties, you are: (i) looking at the wrong dynamic parameter; (ii) not considering the entire system; or (iii) not evaluating at a system at all. We suggest that our focus should instead be on the relationships between components, complexity, and function. Using this as a basis for a new framework will allow us to assemble and align disparate threads of soil science into a cogent and coherent "new theory of soil health", which is an essential and practical step forward for the sustainable management of global soil resources, across all land uses.

Highlights

- The term "soil health" is widely used, but understood and used in different ways.
- Health is a characteristic of an identifiable entity – usually an organism or discrete system.
- To identify and measure soil health we need to discover its system properties and their dependence on complexity and connectivity.
- The scale at which system properties emerge is currently unclear.
- We suggest a broad programme of research to identify dynamic emergent properties, especially resilience, in order to determine soil health.

KEYWORDS

dynamic properties, emergent properties, resilience, scale, soil health, systems

1 | INTRODUCTION

In recent years, there has been surging recognition about the importance of soils (Cimpoiasu et al., 2021; Evans et al., 2021; Keesstra et al., 2016). Soils have always been a fundamental part of terrestrial ecosystems, supporting functions and biodiversity and key in food production, storing and cleaning water, accumulating carbon, regulating climate, safeguarding energy, providing raw materials, and supporting critical infrastructure (Blum, 2005). However, as we confront a burgeoning number of global challenges such as the climate emergency, a biodiversity crisis, and land degradation impacting on food security, our dependency on soils to continue delivering these services intensifies. Acknowledging a critical responsibility to ensure soils maintain this capacity, scientists, policymakers, and stakeholders alike have recently become motivated to develop a tool to assess the beneficial or degradative effects of land use and management on soil characteristics—often given the label "soil health".

Soil health is a metaphor widely adopted by the scientific community in the 1990's (Powlson, 2020), although it was first used in print as early as 1910 (Brevik, 2018). It has proved a powerful tool in conveying best practice to lay audiences, and is increasingly found in international fora, strategic programmes (e.g. Soil Health and Food Mission, the Soil Health Institute, the Soil Biology and Soil Health Partnership, UK 25 Year Environment Plan), agreements and long term plans (Jian et al., 2020). Soil health is often used synonymously with terms such as "soil quality" and "soil fertility", although some have demonstrated a preference for health as soil is perceived as a living system (Powlson, 2020; Wood & Litterick, 2017). However, its widespread adoption has subsequently led to calls by many public bodies for tools that can measure soil health, preferably quantitatively, and often using a single figure, for ease of use/communication and cost of monitoring.

To this day, establishing how to measure 'health' in living organisms still incites debate, although its etymological origins in the Old English "hælth" meaning "wholeness" is reflected in a general acceptance among the medical profession that health cannot be represented by one property, organ, or function alone (Brussow, 2013). Instead, health manifests as a product of multiple characteristics. In recent decades, the term 'health' has also been used to describe the ability of an organism to maintain these characteristics through changing circumstances ("allostasis", see Huber et al., 2011). In complex systems, this adaptive capacity is exhibited in "emergent" properties such as resilience in the face of perturbation.

The insurmountable problem is that soil is not a living organism where health can be readily measured and quantified. Instead, soils are a conglomeration of biotic and abiotic solids (organic and inorganic), liquids, and gases that perform multifarious functions at a range of spatial and temporal scales, orchestrated by biological organisms and regulated by environmental and geographical conditions. Therefore, our challenge is to conceive the most effective ways of deploying a metaphor like "soil health" for the purposes of soil monitoring and management so it can be readily understood and adopted by governments and stakeholders, whilst safeguarding the underlying scientific veracities and fundamental understanding upon which it is based.

There still remains a great deal of active discussion as to what "soil health" actually means and how it should be measured (Baveye, 2021). Some researchers have suggested that the components underpinning soil health are well known, and comprise aspects of the three major scientific divisions of soil chemistry, biology, and physics; instead, the challenge is finding agreement about the standard soil tests that are required to measure these (Wood & Litterick, 2017). Back in 2010, Addiscott (2010a, 2010b) suggested we should look at characteristics as change in entropy, and the ratio of small to large molecules in soils as indicators of the condition. Others, such as Janzen et al. (2021) have argued that soil health cannot be measured per se but that properties can be used as "illuminating indicators" which should be projected through the lens of land functions (e.g., food quality, water quality, climate mitigation) and societal values (e.g., aesthetics, equity, well-being), an activity which, they suggest, should enlist the support of those within the social sciences and humanities. This is echoed by Lehmann et al. (2020) in their comprehensive history and critique of the notion of soil health, where they stress that embracing it as an overarching principle is essential, and that ecosystem service provision should be incorporated as a further dimension for understanding the importance of soil in delivering sustainability goals, not just as another environmental measurement. They highlight the difficulty in coming to cogent soil health indicators as most measurements deployed to date have been chemical indices.

These publications serve as useful commentaries and critiques on what may be called "the conventional approach" to soil health. To summarise, the conventional approach of describing 'soil health' has focussed on simple, in-situ, point-based measurements of key "proxy" variables (e.g., soil carbon stocks) or studying basic sub-component interactions (e.g., colloid to mineral, microbe-nutrient). Over recent decades these techniques have evolved with varying levels of sophistication and complexity (Neal et al., 2020), spurred, in part, by a wave of innovations in metagenomics, sequencing, and informatics (Evans et al., 2021). Indeed, Powlson (2020) asserts recent technological innovations have enhanced our capabilities to conduct not only measurements of soil properties, but continuous or routine soil monitoring which can assist farmers with their in-season and long-term decision-making and, at larger scales, detect trends not so easily discernible at the individual farm scale. However, these singular measurements—or combinations thereof—do not permit us to comprehensively assess the "health" of the whole soil system. Therefore, we posit a paradigmatic shift away from this atomized focus on selected state variables towards a holistic approach that identifies and assesses key measures of system organisation in soils. We argue for a true whole system study, which critically explores the relationships between components, complexity, and function. Only by doing this will we be able to detect signals of emergent properties.

2 | IS SOIL A SYSTEM? THE IMPORTANCE OF SCALE

We argue that the only way to detect "soil health" is to adopt a whole system approach. This requires two distinctive departures from the way that soil health has been assessed to date. First, the scale of inspection must be sufficiently large to capture the entire system, if it exists, in contrast with commonplace practices that narrowly focus on a shortlisted range of indicator properties (e.g. soil structure, soil carbon, soil pH). Second, the methodology must be able to detect the relationships between components, the feedbacks between functions, and the resultant complexity and emergent properties (such as a return to a previous functional or structural state after disturbance; synchronisation of biotic-abiotic interactions; pattern formation; Crawford et al., 2011) and the scale at which they emerge, if at all (Figure 1). This is essential as these signals of emergent properties are the closest indicators of the health of the *whole* soil system. We argue that if the emergent properties of a complex system are not detected, (i) the wrong dynamic parameter is being observed, (ii) the whole system is not being observed; or (iii) one is not observing a system. Therefore, some scales of inspection, especially taken at a single time point, will not be able to detect a soil system, but simply sub-components of it—and if larger and larger scales of inspection fail to detect dynamic emergent properties, then we cannot claim that soil is a system at all.

3 | PROPOSING A NEW THEORY FOR SOIL HEALTH

We propose a whole system approach for assessing soil health, based on a new hierarchical framework of soil system organisation. This framework, embracing interrelated signs of life, function, complexity, and emergence, reflects a hierarchy of increasing organisation and ecosystem development, which are arguably recognisable characteristics in ecological succession.

- *Signs of Life*: characterising the simple communities that exist in soil to those which are more complex (e.g., DNA, metagenomic community diversity, volatile organic carbon profiling).

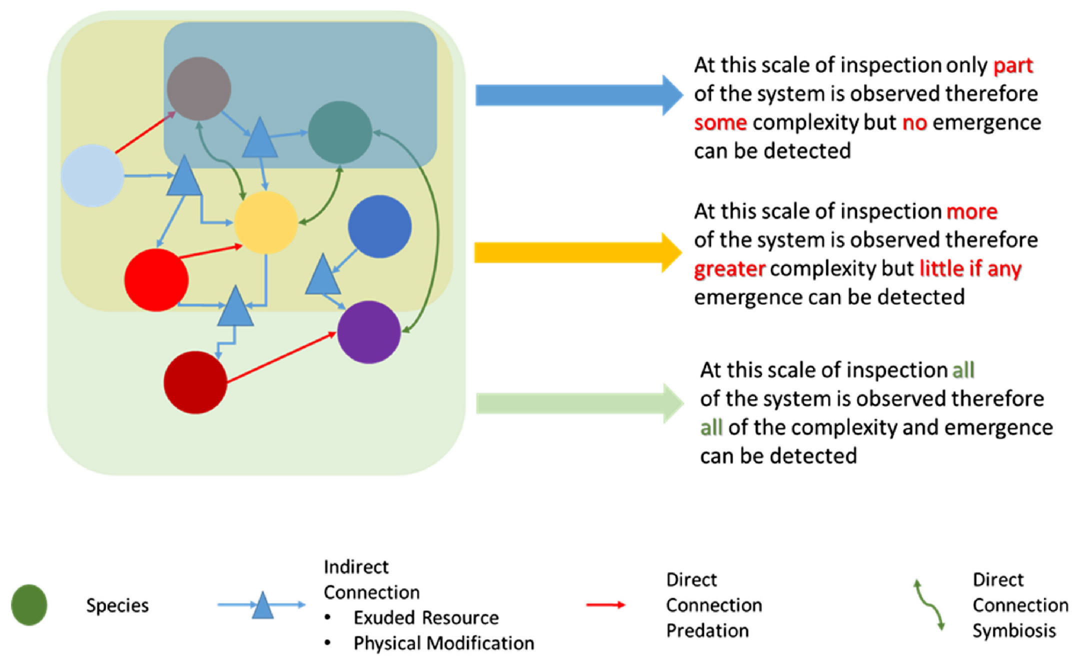

FIGURE 1 The importance of scale of observation to capture system-level properties

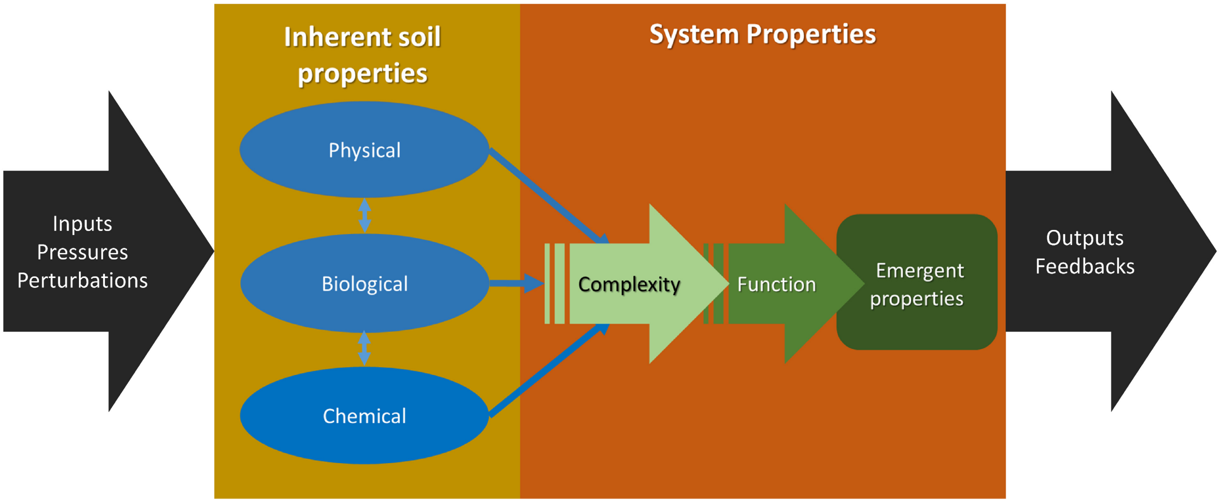

FIGURE 2 A putative relationship where inherent soil properties interact to produce complexity which determines function and produces emergent properties, with the relation of the system to the external environment.

- *Signs of Function*: characterising the ability of a soil to perform a limited number of simple transformations, towards a rich and diverse set of functional traits, with extensive functional redundancy and multiple functions (e.g., catabolic profiling, thermodynamic efficiency).
- *Signs of Complexity*: characterising isolated individuals and populations to highly connected and interdependent communities, which are active across different scales (e.g., community trophic structures, large:small molecule audits).
- *Signs of Emergence*: characterising the resource- and function-limited largely inert mineral substrate to a multi-faceted, biodiverse system capable of recovery when subject to multi stressors (e.g., recovery response to repeated perturbation).

We suggest that these parameters capture what we need to know to identify soil as a system, and how the integration of soil physical, chemical, and biological properties are combined in a connected complex way from which function and emergent properties arise (Figure 2).

For our framework of soil system organisation, we can be inspired by the many ways in which the emergence of scale, multifunctionality, and self-organisation in complex systems over time has been described and measured in other fields (Table 1). These are rich areas for investigation, currently understudied in soil science.

4 | A MANIFESTO FOR RESEARCH: NEXT STEPS AND OPEN QUESTIONS

Assessing soil health through the interconnected lenses of life, function, complexity, and resilience provides the bedrock for a new manifesto of research. There are undoubtedly significant research gaps and innovation opportunities for each lens.

To study "signs of life", we must first ask how we can best characterise and identify the biology of soils, unambiguous signals of diversity, activity, and interactions with implications for function, as well as determining the extent to which soil biology is simple or complex, stochastic or determinist.

To assess the "signs of function" in soils, research is required to identify the multifarious ways in which soil ecosystems transform energy and materials across different spatial and temporal scales, and assess their efficiency in doing so. Understanding how soils respond to different types of system inputs, including both new abiotic, biotic, and structural information, is key.

As well as signs of life and function, new research to identify the "signs of complexity" is also warranted. Herein lie many fundamental questions about the feedbacks and connectivity that may manifest between the signs of life and function in soils. For example, how can we best characterise the complex relationships and feedbacks across biotic and abiotic interfaces in the soil system, including the intersections between soils and plants, fauna, rocks, water, and air? A soil in the early stages of development, harbouring simple ecological communities (e.g., pioneer species), may arguably both require and deliver relatively few functions. These pioneer species may initially appear to exist in isolation, but will adapt into more complex communities when they become connected, adapting their immediate and surrounding environment, as they must do to persist, since no organism holds the information it needs for survival. The result of this connectivity is that the soil system becomes more complex than the sum of its parts.

TABLE 1 Examples of system properties from ecological studies

System organisation	Examples	References
Collective behaviour	Synchronisation	Detrain and Deneubourg (2006) Perna and Theraulaz (2017)
	Swarm behaviour	Mazzolai et al. (2010) Beekman et al. (2008)
Networks	Graph theory	Gao et al. (2018) Green et al. (2018)
	Adaptive networks	Nuwagaba et al. (2017) Raimundo et al. (2018)
Evolution and adaptation	Genetic algorithms	Mitchell (1996) Sivanandam and Deepa (2008)
	Machine learning	Michalski (2000) Wu et al. (2019)
Pattern formation	Dissipative structures	Goldbeter (2018) Tlidi et al. (2018)
	Spatial fractals	Halley et al. (2004) Keshavarzi et al. (2018)
Systems theory	Homeostasis	Spohn (2016) Eskov et al. (2017)
	Information theory	Griffiths and Hochman (2015) Nozaries et al. (2021)
Non-linear dynamics	Population dynamics	Holland et al. (2002) Stucchi et al. (2020)
	Time series analysis	Kantz and Schreiber (2003) Clark and Luis (2020)
Game theory	Co-operation vs. competition	Ghoul and Mitri (2016) McNamara and Leimar (2020)
	Prisoners Dilemma	Antonovics et al. (2015) Anten and Chen (2021)

Identifying emergence in systems is the fourth and final area of this new manifesto. Developing techniques and tools to characterise these so-called "signs of emergence" should become a principal goal for holistically assessing the vitality of soil systems, going forward.

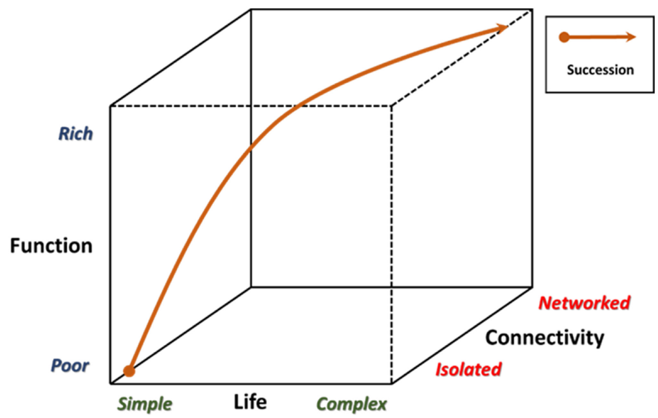

FIGURE 3 Relationship between complexity of life, function and structure—the trajectory suggested is that changes occur during succession with maximum resilience observed in the middle of the trajectory

Elucidating the resilience of the relationships of soil systems in the face of short- and long-term perturbations is a good place to start, as fruitful avenues of approach are tentatively appearing in the literature (e.g. Todman et al., 2018). We suggest that a set of relationships will emerge as systems mature (Sensu Odum), which would include, for example successional gradients and ecosystem restoration projects (Figure 3):

As the system moves from the bottom left to the top right of Figure 3, resilience (an emergent property) increases to the centre of the curve, until the system becomes stagnant at the top right (cf Ulanowicz et al., 2009).

This will certainly require new interdisciplinary collaborations to measure "persistence" in soil systems, and methods to detect when soils are approaching and/or have crossed tipping points to alternate stable states. Furthermore, monitoring temporal changes in resilience as soils develop feedbacks, functions, and connectivity is also essential: does resilience (and other emergent properties) increase as simple, poorly functioning, disconnected systems transform into complex, richly functioning, highly connected systems, and how do we know that functions are developing? Do functions appear and evolve with the system, and how do they contribute to emergent properties in general? By reinforcing their own resilience, to what extent can soils (re)configure or modify their own tipping points? Moreover, can soils pre-empt a perturbation as a form of learned behaviour? Is there a "sweet spot" along the spectrum of developing diversity and connectivity, as Fath et al. (2019) suggests for socio-economic systems, beyond which they become stagnant—and resilience changes from "helpful" resilience which returns the system to the state of healthy vitality, to "unhelpful" resilience which keeps the system in a stagnant state, with lower function, fewer connections, and reduced biodiversity (Standish et al., 2014).

In conclusion, we suggest that this new theory of soil health, focusing on the signs of life, diversity, function, complexity, connectivity and, most importantly, resultant emergence in soils, offers a foundation for future research programmes with a rich set of hypotheses to test. Dynamic measurements of complex system characteristics will provide a clear indication of the integrity and function of the soil being assessed, based on fundamental understanding of the mechanisms and interrelationships in play. The aim is not to provide an immediate set of tools for use by the practitioner community, but rather to set out a new research vision to be explored in order for such useful tools to be developed. Our suggested approach provides a necessary practical step forward to holistic measurement of soils to provide governments and land users with the metrics essential to sustainably manage global soil resources for future generations.

AUTHOR CONTRIBUTIONS

James A. Harris: Conceptualization; Writing - original draft; Writing - review & editing; Visualisation; Project administration. Daniel L. Evans: Conceptualization; Writing - review & editing; Writing - original draft. Sacha Jon Mooney: Conceptualization; Writing - original draft; Visualisation; Writing - review & editing.

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CONFLICT OF INTEREST

There are no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

ORCID

James A. Harris https://orcid.org/0000-0001-9266-4979
Daniel L. Evans https://orcid.org/0000-0002-4484-7874
Sacha J. Mooney https://orcid.org/0000-0002-9314-8113

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