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Soil Health – It's Not All Biology

Mark S. Coyne
University of Kentucky, mark.coyne@uky.edu

E. M. Pena-Yewtukhiw
West Virginia University

John H. Grove
University of Kentucky, jgrove@uky.edu

A. C. Sant'Anna
West Virginia University

D. Mata-Padrino
West Virginia University

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M.S. Coyne [a,*], E.M. Pena-Yewtukhiw [b], J.H. Grove [a], A.C. Sant'Anna [b], D. Mata-Padrino [b]

[a] Department of Plant and Soil Sciences, University of Kentucky, Lexington, KY 40546-0091, USA
[b] Davis College of Agriculture, West Virginia University, Morgantown, WV, USA

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ABSTRACT

Soil Health research tends to bias to a biology/microbiology emphasis. We believe this bias neglects important physical and chemical interactions in soil that are crucial to soil function. We offer several examples illustrating this bias, and how it may misrepresent management practices that have the greatest influence on Soil Health. Four suggestions are given as approaches to mitigate this bias. By appreciating soil structure as a foundation for Soil Health and its microbial community, we believe better recommendations can be made to assist the farm community in its stewardship of soil as a critical natural resource.

1. Why soil health?

Soil Health is the sustainable capacity of soil to function as a vital living system, recognizing that soil contains biological elements that are key to ecosystem function within land-use and ecosystem boundaries. It is intuitive that an unhealthy soil cannot support a healthy ecosystem either above or below ground: they are inextricably linked. Because 'WE' are among the animals that soils support above ground, it is in our best interests to make sure soils continue to provide this service. The initiatives for enhanced Soil Health in the Natural Resource Conservation Service (NRCS) and Soil Health Institute (SHI) that promote suites of practices targeting physical, chemical, or biological management illustrate this interest.

Biological management is a favorite target because its effects are often (but not always) observed, and observed quickly (Doran and Zeiss, 2000). *But there is a problem with this approach.* At least a problem with having too blinkered a focus about soil biology's significance. It is one thing to value soil biology as an indicator of Soil Health and quite another to consider its targeted management, particularly with respect to its microbiology. We have been down this road before. Believing a causal relationship exists between microbes and some environmental phenomenon, whether it is disease or yield or some other activity associated with soil ecosystem functions. Presence may be an artifact of the environment; a commensal response sufficiently common to be a 'general result' of environmental change. Presence does not mean causation. Presence may be necessary, but not sufficient (Fierer et al., 2021).

Not withstanding the excellent work performed in soil biology that distinguishes communities and their function, we suggest (from our various physical, chemical, and microbiological perspectives) this approach as an end in itself, will not have the utility one might like it to have in making significant contributions to Soil Health improvement, unless it is more closely tied with an appreciation of the physical and chemical millieu. We advocate for greater transdisciplinary collaboration among our colleagues in soil science to address critical soil management needs in a changing global environment. And we are mindful of the cautionary warning (which persists in agriculture) that effortless changes to soil properties, particularly by adding novel microbial amendments, deserve the skepticism they raise. If it seems too easy, it probably is – *caveat emptor*.

2. What illustrates the danger/risk of overemphasizing microbial solutions to soil health issues?

We provide several examples prevalent in the literature: scientific and popular, written and multimedia. There is a tendency to believe in an ideal microbial composition without considering other soil properties. That if one could only re-create particular microbial ratios or the representation of certain micro, meso, and macro populations, then a soil would be restored to health. The baseball fan knows that in "Damn Yankees" ALL that kept the Washington Senators from the pennant was one long ball hitter (Wikipedia, accessed November 2021). Except that such microbial ratios are spatially, temporally, and most likely scale dependent. To create an ideal population mix in a soil environment from which that mix is supposedly absent assumes: (1) that there is an ideal ratio; (2) you can be unbiased sampling or measuring it; (3) that there is

* Corresponding author.
E-mail address: mark.coyne@uky.edu (M.S. Coyne).

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not some feature of the environment causing population disparities to exist in the first place; (4) that introduced populations survive in anywhere close to their existing ratios – there are many ways microbes can die in soil; (5) that sampling time is inconsequential, which Muratore (2019) and Liu et al. (2018) have shown to be false; (6) that one knows which soil property(ies) keeps/are keeping one or more constituents of an ideal population from manifesting themselves.

There is a tendency to conflate/confound/confuse the presence and expression of activity *in vitro* with its actual significance *in situ*. Koch and Pasteur both erred in carefully isolating and cultivating commensal organisms with no association whatsoever to disease. One need look no farther than research on optimal pH for nitrification to realize that, removed from their soil habitat, lithotrophic bacteria responsible for nitrification have quite different pH optima than their soil counterparts. That these bacteria also have a much higher K_m for NH_3 than their archaeal counterparts greatly explains how generations of nitrification research focused on the model lithotroph, *Nitrosomonas europaea,* which was neither the most numerous nor the most active of the soil nitrifiers, but *was the most culturable artifact* of isolation in a high NH_4^+ environment. It does not follow that if you can isolate it, it must be important. This assumes you can isolate it; there are many ways by which microbes live that we have not yet figured out. Metagenomics suggests a great deal of potential underlying microbial activity in unculturable populations (Sun and Badgley, 2019).

However, there is also a tendency to believe that microbial diversity, as revealed by molecular methods, is a suitable proxy for the capacity of soil to function as an integrated unit. It is assumed that greater diversity must mean greater capacity; perhaps not (Fierer et al., 2021). The Microbiome Stress Project revealed that too little diversity mitigated against community resistance to stress, but so did too much diversity (Rocca et al., 2019). Plant rhizosphere research constantly indicates the rhizosphere neighborhood may not merely be selective, it may also be discriminatory (Kavamura et al., 2020). The metagenome shows the same dominant prokaryotic phyla appear in most soils; the transcriptome, that a multitude of functions are induced in individual prokaryotes (Dar et al., 2021), though depending on location not necessarily contributing to processes of interest. The metabolome shows that products are made *in situ*, but whether they have functional significance for the active populations rather than constituting overexpression by a minority of organisms remains to be demonstrated. (Though functional significance of metabolome products may occur, as Raczka et al. (2021) seem to demonstrate with 13C-labeled substrates in forest ecosystems.)

We must always be on guard against believing that genomic characterization of soil biology based on genetic sequences derived from cultured organisms adequately represents the unculturable 99% of the population. To use the 1% analogy, if an alien civilization were to base its understanding of the biology and sociology of any country on its wealthiest 1%, what would they deduce? Further, there can be a tendency to ignore trophic levels above and below the specialization we follow.

For simplicity, there is a tendency to believe soil structure is invariant seasonally rather than plastic. Considering the energetic exploration of soil by plant roots and fungal hyphae, it seems unlikely individual aggregates of a given size represent a consistent habitat. Stable aggregation should really be called "dynamic-stable aggregation." The bigger aggregates include physicochemical bonds (among ions, mineral clays, and amorphous oxides - these all tend to be very stable) but they are surrounded by, and interacting with, temporary and transient bonds that constantly change (some faster than others). Multiple changes together can cause "no change," which is the stability we measure, and that represents the plasticity of aggregation. Alone, biology cannot explain this phenomenon. Making assumptions and doing research based on that premise is a mistake, particularly with respect to dynamic microbial populations in a plastic soil environment.

There is a tendency to forget how much soil chemistry and physics matter, especially at scales relevant to microbial growth and colonization. Microbes must still compete with the soil mineralosphere for nutrients; diffusion of water and gas greatly matter at the scale of the soil aggregate.

And yes, there is still a fuzzy definition of Soil Health and how to evaluate it (Wander et al., 2019). Lord Kelvin wrote, "science is numbers," to which the soil chemist Grant Thomas added, "Good science is good numbers – occasionally real numbers" (Thomas, 1992). If you can measure it, you can quantify it. But quantification in terms of Soil Health – the Holy Grail of an index that scales soil environments – has little value if a given number in a given setting lacks relevance to the controlling factors of soil function in those settings; the number does not really reflect the true state of soil.

3. What should be done?

Biology is only one factor more, not the "driver' of Soil Health. Soil Health does not rotate around biology however much microbiologists would like to believe otherwise from a professional and financial (grant funding) perspective. There is always great benefit in the active collaboration of multiple disciplines to investigate Soil Health.

- We need change in research premises to provoke researchers to question what we and our colleagues (soil scientists) are doing, or not doing, because of our disciplinary focus.
- We must think about the *in situ* significance of specific microbial groups and functions (Barnett et al., 2021).
- We must consider that weather and soil physical characteristics (in combination with plants and management) control air, water, and carbon dynamics (differences reflected spatially within and outside the soil - vertical and horizontal variability) and this effect of air, water, and carbon dynamism has not been well explored when Soil Health is discussed (Wang et al. 2019).
- We need real transdisciplinary teams to interact in examining the interplay of physical, chemical, and biological properties in soil. After all, "phenotype depends on environmental context" (Li et al., 2019). While the "microscale context is what matters to microbes" (Diann Newman, Cal Tech), microscale matters far less than higher level soil structure to macrofauna and plant roots. Transdisciplinary teams will facilitate recognizing and appreciating knowledge from allied disciplines at multiple scales.

4. Why is this important?

Agriculture, and by association - farmers, are in the dubious position of responding to the effects of climate change while simultaneously being blamed for climate change, and yet are positioned to mitigate and militate some of the worst effects of climate change – anthropogenic or otherwise (Mubiru et al., 2017). What are farmers to do? What advice and support can investigative science with respect to Soil Health provide that is feasible and consequential?

Waksman (1927) was prescient in arguing that among the most important questions future soil microbiologists should address is "how soil organisms are affected by their physical environment and how, in turn, do they modify their physical environment?" We might also ask the question "where" they are active because that question is at the heart of recent research on the accessibility of complex soil C to microbial decomposition (Lehmann and Kleber, 2015) and how that influences microbial community structure and activity (Barnett et al., 2021).

Soil is a "field of dreams" - if you build it, they (the biology) will come. It is inevitable. The biology does not need training to occupy the ecological niches it inhabits. As with any real estate – location, location, location. Good infrastructure (aggregation) and good services (aeration, hydration, nutrition, etc.) make for a good neighborhood. While we debate the necessity of Soil Health to preserve the many soil functions that enable us to live, we must not forget that no amount of biology and particularly microbiology can restore an environment that no longer exists. No biology or microbiology can be properly understood, appreciated, or investigated without consistently recognizing the chemical and physical context in which it exists.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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