

Sustainable Soil Health

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Healthy soils are the foundation for meeting the increasing world population's needs for food, fiber, nutrition, and healthy environment on a limited landmass further confounded by climate change grand challenge that requires multi-dimensional solutions.

agriculture

degradation

ecosystem services

fertilizer use efficiency

nematodes

nutrient cycling

soil amendments

soil food web

1. Introduction

1.1. What Are the Characteristics of Sustainable Soil Health?

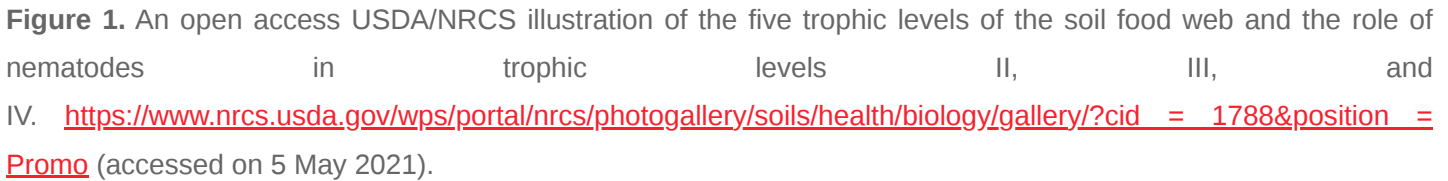
Healthy soils are the foundation for meeting the increasing world population's needs for food, fiber, nutrition, and healthy environment on a limited landmass further confounded by climate change grand challenge that requires multi-dimensional solutions ^{[1][2][3][4][5][6][7][8]}. Soil health—the capacity of a soil to generate desirable ecosystem services—requires a dynamic balance among biological, physiochemical, nutritional, structural, and water-holding components ^{[1][9][10][11][12]}. Developing a sustainable soil health for both agricultural (*annual to perennial; row and non-row crops*) and managed natural (*forests, grasslands, rangelands*) production systems is central to meeting both food demands and to reducing environmental damage ^{[3][5][6][10][13][14][15]}. In this context, we define sustainable soil health as one that simultaneously generates three sets of desirable ecosystem services ^{[9][12][16][17][18][19][20][21][22][23][24][25]} while meeting environmental and economic expectations ^{[5][26][27][28][29][30]}. These three sets of desirable ecosystem services are to: (i) improve soil structure, physiochemistry, water-holding capacity and nutrient cycling; (ii) suppress pests and diseases while increasing beneficial organisms; and (iii) improve biological functioning leading to improved biomass/crop yield, simultaneously. When soil health is out of balance, it becomes difficult to generate the desirable ecosystem services ^{[10][11][12][13][27][28][29][30][31][32][33][34]}.

The objectives of this review are two-fold: First is to identify barriers to developing sustainable soil health through a conceptual understanding of agriculture's footprint in the cycle of soil health degradations; and second is to describe how nematode-based soil food web (SFW) ^[34] and fertilizer use efficiency (FUE) ^{[28][29][30]} models can serve as integrated soil health management decision-making tools. The SFW model uses changes in population dynamics of beneficial nematodes to identify best-to-worst outcomes for agroecosystem suitability. The FUE model uses beneficial and harmful nematodes to identify if the outcomes meet the definition of sustainable soil health. This review highlights how these two models can serve as a platform towards developing integrated and sustainable soil health management strategies on a location-specific or a one-size-fits-all basis.

1.2. Why Nematodes Are Important to Soil Health?

Nematodes, non-segmented worm-like organisms, are present in all ecosystems, are sensitive to disturbance by agricultural practices (APs), and represent 80% of metazoans on the planet [\[11\]\[33\]\[34\]\[35\]\[36\]](#). Based on their food source, soil-dwelling nematodes are classified into trophic groups that include bacterivores (*bacterial feeders*), fungivores (*fungal feeders*), plant-parasites or herbivores (*plant-feeders*), predators (*feed on nematodes and other life forms*), and omnivores (*feed on a range of soil organisms*) [\[36\]](#). The nematode trophic groups have life histories and reproductive strategies that fall into five categories commonly known as colonizer-persister (c-p) groups [\[34\]\[37\]\[38\]\[39\]](#). These range from c-p 1, *fast reproducing and tolerant to disturbance*, to c-p 5, *slow-reproducing and sensitive to disturbance*. The c-p groups have different functions. Bacterivores, fungivores, omnivores, and predators are all beneficial and pertinent to nutrient cycling and maintaining healthy soils [\[10\]\[11\]\[12\]\[21\]\[36\]](#). It is important that a healthy soil contains all c-p groups of all beneficial nematodes. Herbivores, which use a stylet (*resembles a flexible hypodermic needle*) to pierce roots (*root parasites*) or leaf tissue (*shoot parasites*) to obtain nutrition, are harmful pests that cause crop yield loss. Herbivorous and beneficial nematodes exist in the same soil ecosystems. Change in nematode population dynamics is an excellent indicator of changes in soil and global ecosystems [\[11\]\[33\]\[35\]\[36\]](#).

Another way that nematodes are important to soil health is in nutrient cycling within the functions of the SFW ([Figure 1](#)). As shown in this open-source USDA/NRCS figure, nematodes are a critical part of the SFW in Trophic Levels II, III, and IV of the SFW ([Figure 1](#) [\[10\]\[11\]\[21\]\[34\]\[40\]\[41\]\[42\]\[43\]](#)). Level I are the photosynthesizers, Level II are decomposer and parasites, Level III are shredders, Level IV are predators, and Level V are higher level predators. In simple terms, the desired ecosystem services from a functioning SFW are the predator-prey and excretions of many micro- and macro-organisms operating across five trophic levels. By feeding on or being food for other organisms, nematodes contribute to releasing nitrogen and nutrient cycling in general [\[12\]\[21\]\[40\]](#). A combination of their presence in all ecosystems, role as nutrient cyclers in the SFW, and sensitivity to APs-driven disturbances make nematodes excellent bioindicator organism to develop sustainable soil health in cropping systems.



Agriculture has a substantial footprint relevant to soil health and ecosystem degradation. For example, agriculture contributes ~84% of the global nitrous oxide (N₂O) emissions [4]. In addition, soil fertility (organic and inorganic forms) managements [22][26][44][45][46][47][48], pesticides and agricultural inputs [19], land use (tillage, grazing) practices [2][17][18], and cropping systems [16][47][48] are among the APs that directly or indirectly influence the soil health components and in variable ways [45][46][47][48][49][50][51][52][53]. Although global fertilizer application will exceed 200 million metric tons per year [54] and the negative effects on soil health and the environment will continue, there are regional differences. For example, in economically less developed parts of the world, fertilizer may be expensive and soil health degradation may be exacerbated from inadequate soil fertility management. In economically developed countries, lack of integrated fertilizer use efficiency leads to nutrient pollution and economic waste [25][26]. For example, a comprehensive study of N use and maize and soybean yield in the U.S. Midwest showed a disturbing picture [26]:

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- Total loss to farmers from overfertilization in low- and variable-yielding areas was ~\$485 million. The loss in fertilizer value corresponded to greenhouse gas (GHG) of 6.8 MMT CO₂ equivalents.

It is clear that current fertilizer use practices and APs' impact on soil health degradations are unsustainable. To reverse the trajectory of unsustainable practices and improve APs and soil health, in-depth understanding of the impact of APs' large footprint on soil health and associated management decisions is necessary.

2. Conceptual Understanding of the Cycle of Soil Health Degradation

How efficiency and sustainability of the impact of APs' on generating desirable ecosystem services are assessed are contributing factors in the cycle of soil health degradation. [Figure 2](#) depicts a conceptual view of how separate APs or AP combinations applied in production systems (A) will alter soil health components (B) in generating objective-dependent ecosystem services (C), and the basis for management decisions if the outcomes of the objectives were either yes, no, or variable for one or more ecosystem services (D). A common way to determine whether APs generate desired ecosystem services is to assess production efficiency (E) and sustainability (F) of the outcomes. A combination of the gaps in integrated understanding of the process-limiting dynamics affecting A, B, and C, and the lack of decision-making tools affecting D, E, and F, creates bottlenecks that continue the feedback cycle of soil health degradation. Using soil fertility management applied to increase biomass/crop yield and/or suppress harmful plant-parasitic nematodes (PPN) as examples, we define production efficiency in this context as the difference between the values of inputs (e.g., soil amendment or fertilizer) and outcomes (e.g., yield increase and/or suppression PPN, or both) [\[11\]\[44\]\[55\]\[56\]\[57\]](#).

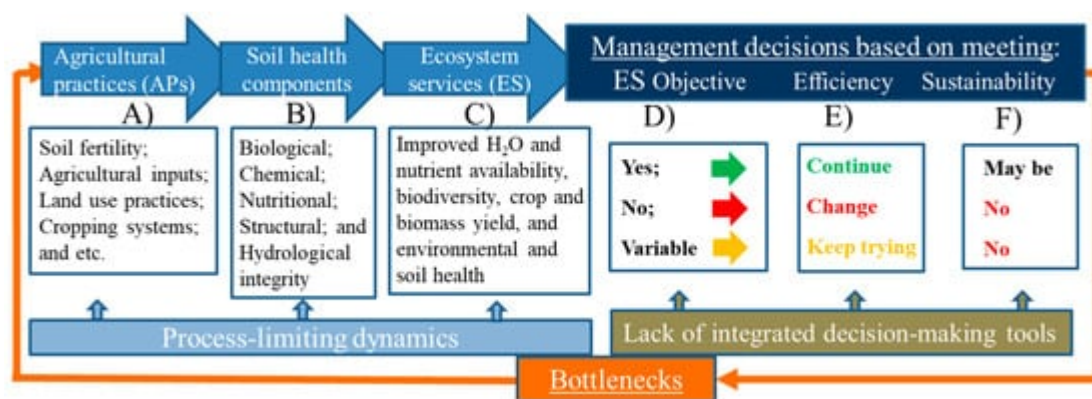


Figure 2. Key concepts in crop production management: (A) agricultural practices (APs) collectively influence, (B) soil health components to generate (C) objective-dependent ecosystem services (ES) outcomes, that (D) may be achieved (yes) or not achieved (no) or variably achieved, which lead to management decisions on (E) efficiency and (F) sustainability of the outcomes, and the bottlenecks in the gaps in integrated understanding of the process-limiting dynamics across A, B, and C, and the lack of decision-making tools across D, E, and F, that keep the cycle of soil health degradation continue.

As depicted in [Figure 2](#)E,F, only yes or positive outcomes are seen as efficient and sustainable, so that soil treatments continue when an outcome is positive (green arrow), change when an outcome is negative (red arrow), and either change or continue with hope for better results when an outcome is both yes and no (yellow arrow). In the meantime,—because efficiency analysis based only on PPN suppression and/or increased biomass or crop yield does not always provide insights useful for system sustainability decision making—soil degradations continue unaddressed. For example, a soil nutrient amendment may not be sustainable if the amendment increases crop/biomass yield but adversely affects the soil environment [\[13\]\[57\]](#) or beneficial soil organisms [\[2\]\[28\]\[29\]\[30\]](#). *Under these circumstances, conclusions from [Figure 2](#) outcomes are likely to remain discipline-based comparisons between an independent variable (AP treatment) and dependent variable (ecosystem service) in space and time [\[11\]\[44\]\[55\]\[56\]\[57\]](#).* This limitation makes it difficult to achieve sustainable agroecosystem and soil health conditions because the effects of APs (A) on the soil health components (B) necessary to generate the desired ecosystem services (C) might be subjects of study of not one but multiple disciplines ([Figure 2](#)). Sustainable soil health management is unlikely to be achieved without an integrated and interdisciplinary understanding of the process-limiting factors affecting the generation of desirable ecosystem services and identifying and/or developing management decision-making tools that aid in translating basic science into practical application.

3. Barriers to Developing Sustainable Soil Health and How to Overcome the Gaps Using Nematodes

There are several barriers to aligning sustainable soil health with the desirable ecosystem services.

First, despite a considerable basic and applied soil health knowledge, it is rare that management strategies align soil health components and the ecosystem services they generate [\[46\]\[58\]\[59\]\[60\]\[61\]\[62\]\[63\]\[64\]\[65\]\[66\]\[67\]\[68\]\[69\]\[70\]](#). Occurrence of beneficial and pathogenic organisms in the same soil environment further complicates aligning desirable ecosystem services [\[13\]\[28\]\[29\]\[30\]](#).

Second, there are no quantitative benchmarks for the functions and process-based outcomes across the desirable ecosystem services that describe what a steady-state soil health looks like for any AP, soil type, or cropping system [\[13\]\[31\]\[32\]\[33\]\[47\]\[48\]\[49\]\[50\]\[51\]\[62\]\[71\]\[72\]](#).

Third, lack of integrated translation of the biophysicochemical-based outcomes in ways growers can easily understand. Practical application is difficult.

Fourth, there is no framework for alignment of multiple ecosystem services simultaneously.

There are three major gaps to overcoming the critical barriers to developing steady-state soil health conditions and soil health practices that generate the desirable ecosystem services.

First, the integration of the substantial knowledge on all components of soil health in ways that align the 3 sets of desirable ecosystem services is lacking. The biological component of soil health that drives the belowground

nutrient cycling of the SFW ([Figure 1](#)) and biodiversity [\[10\]\[11\]\[12\]](#) can be a platform for step-by-step integration.

Second, many of the micro- and macro-biome communities in the SFW are used as indicators of soil health [\[72\]\[73\]\[74\]\[75\]\[76\]\[77\]\[78\]](#). However, there is a need for a foundation up on which the biological indicators can be integrated to identify agroecosystem suitability of the APs-driven outcomes. In this case, soil-dwelling nematodes can serve as a model organism, and the nematode community analysis-based Ferris et al. [\[34\]](#) SFW model can be a tool for identifying agroecosystem suitability of AP-driven outcomes.

Third, an outcome that looks suitable for an agroecosystem and efficient by disciplinary measures ([Figure 2D–F](#)) is not necessarily sustainable. For an outcome to be sustainable, it has to meet a balanced expectation of generating the desirable ecosystem services and economic and environmental needs simultaneously. In this case, the harmful and beneficial soil-dwelling nematode community analyses-based FUE models can be a foundation for identifying sustainable outcomes [\[28\]\[29\]\[30\]](#). A combination of the SFW and FUE model analyses can be used to understand the process-limiting factors and gaps in decision-making tools ([Figure 2](#)) and align ecosystem services needed for sustainable soil health management in cropping systems.

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