Sustainable Soil Health

Subjects: Green & Sustainable Science & Technology
Contributor: Haddish Melakeberhan

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.

Keywords: 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.

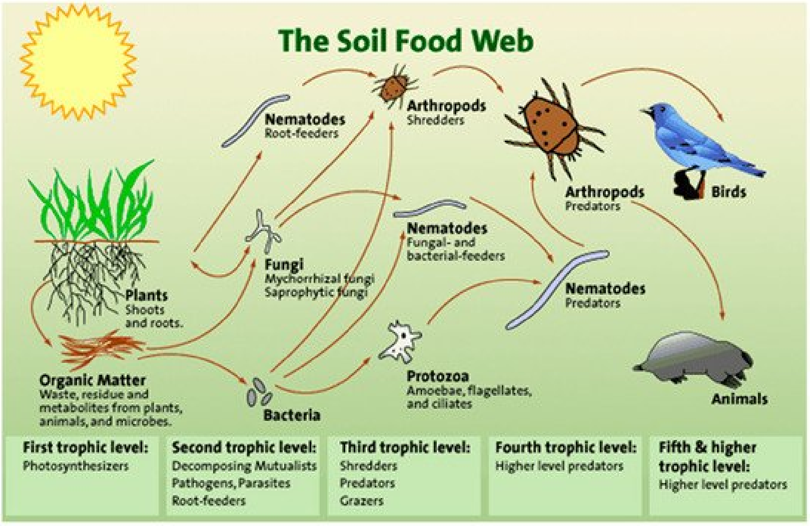

Figure 1. An open access USDA/NRCS illustration of the five trophic levels of the soil food web and the role of nematodes in trophic levels II, III, and IV. https://www.nrcs.usda.gov/wps/portal/nrcs/photogallery/soils/health/biology/gallery/?cid = 1788&position = Promo (accessed on 5 May 2021).

1.3. Agriculture’s Footprint on Soil Health

Agriculture has a substantial footprint relevant to soil health and ecosystem degradation. For example, agriculture contributes ~84% of the global nitrous oxide (N_2O) 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]:

- Approximately 46% of the maize and soybean acreage was high-yielding, 26% stable low yielding, and 28% unstable (variable) yielding.
- Low-yielding areas contributed ~44% and variable-yielding areas during years of poor yield 31% of total N loss to the environment.
- 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 CO_2 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].

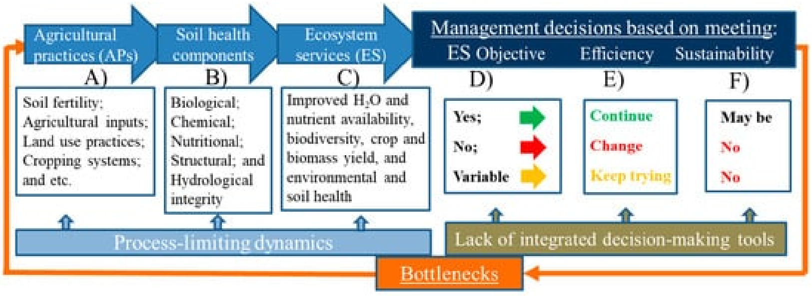

Figure 2. Key concepts in crop production management: (**A**) agricultural practices (APs) collectively influence, (**B**) soil health components to generate (**C**) objective-dependent ecosystem services (ES) outcomes, that (**D**) may be achieved (yes) or not achieved (no) or variably achieved, which 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 2E,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.

References

1. Lal, R. Soil health and climate change: An overview. In Soil Health and Climate Change; Singh, B.P., Cowie, A.L., Chan, K.Y., Eds.; Springer: Berlin/Heidelberg, Germany; Dordrech, The Netherlands; London, UK; New York, NY, USA, 2011; pp. 3–24.
2. Assefa, F.; Elias, E.; Soromessa, T.; Ayele, G. Effect of changes in land-use management practices on soil physiochemical properties in Kabe Watershed, Ethiopia. Air Soil Water Res. 2020, 13, 1–16.
3. Fagodiya, R.K.; Pathak, H.; Kumar, A.; Bhatia, A.; Jain, N. Global temperature change potential of N use in agriculture: A 50 year assessment. Sci. Rep. 2016, 7, 44928.
4. IPCC. Climate Chang. 2013 Physical Science Basis; Contributing Working Group I to Fifth Assessment Representation. Intergovernmental Panel Climate Change 33; Cambridge University Press: Cambridge, UK, 2013.
5. Jankowski, K.; Neill, C.; Davidson, E.A.; Macedo, M.N.; Costa, C.; Galford, G.L.; Santos, L.M.; Lefebvre, P.; Nunes, D.; Cerri, C.E.; et al. Deep soils modify environmental consequences of increased nitrogen fertilizer use in intensifying Amazon agriculture. Sci. Rep. 2018, 8, 13478.
6. Millar, N.; Robertson, G.P.; Grace, P.R.; Gehl, R.J.; Hoben, J.P. Nitrogen fertilizer management for nitrous oxide (N2O) mitigation in intensive corn (Maize) production: An emissions reduction protocol for US Midwest agriculture. Mitig. Adapt. Strateg. Glob. Chang. 2010, 15, 185–204.
7. Pimentel, D.; Giampietro, M. Food, Land, Population and the US Economy. 1994. Available online: (accessed on 19 May 2021).
8. Robertson, G.P.; Bruulsema, T.D.; Gehl, R.J.; Kanter, D.; Mauzerall, D.L.; Rotz, C.A.; Williams, C.O. Nitrogen-climate interactions in US agriculture. Biogeochemistry 2012, 114, 41–70.
9. Anon. Soil Health. NRCS; 2016. Available online: (accessed on 19 May 2021).
10. Doran, J.W.; Zeiss, M.R. Soil health and sustainability: Managing the biotic component of soil quality. Appl. Soil Ecol. 2000, 15, 3–11.
11. Sánchez-Moreno, S. Biodiversity and soil health: The role of the soil food web in soil fertility and suppressiveness to soil-borne diseases. Acta Hortic. 2018, 1196, 95–104.
12. The Soil Food Web and Laboratories in the Continental USA. Available online: (accessed on 19 May 2021).
13. Ferguson, R.B. Groundwater quality and nitrogen use efficiency in Nebraska's central platte river valley. J. Environ. Qual. 2015, 44, 449–459.

14. Lark, T.J.; Salmon, J.M.; Gibbs, H.K. Cropland expansion outpaces agricultural and biofuel policies in the United State s. Environ. Res. Lett. 2015, 10, e044003.
15. Mladenoff, D.J.; Sahajpal, R.; Johnson, C.P.; Rothstein, R.E. Recent land use change to agriculture in the US lake stat es: Impacts on cellulosic biomass potential and natural lands. PLoS ONE 2016, 11, e0148566.
16. Beehler, J.; Fry, J.; Negassa, W.; Kravchenko, A.K. Impact of cover crop on soil carbon accrual in topographically diver se terrain. J. Soil. Water. Conserv. 2017, 72, 272–279.
17. Brainard, D.C.; Noyes, D.C. Strip-tillage and compost influence carrot quality, yield and net returns. HortScience 2012, 47, 1073–1079.
18. Cheng, Z.; Melakeberhan, H.; Mennan, S.; Grewal, P.S. Relationship between soybean cyst nematode Heterodera glyc ines and soil nematode community under long-term tillage and crop rotation. Nematropica 2018, 48, 101–115.
19. Collins, H.P.; Alva, A.; Bydston, R.A.; Cochran, R.L.; Hamm, P.B.; McGuire, A.; Riga, E. Soil microbial, fungal, and nem atode responses to soil fumigation and cover crops under potato production. Biol. Fertil. Soils 2006, 42, 247–257.
20. García-Orenes, F.; Morugán-Coronado, A.; Zornoza, R.; Scow, K. Changes in soil microbial community structure influen ced by agricultural management practices in a Mediterranean agro-ecosystem. PLoS ONE 2013, 8, e80522.
21. Gebremikael, M.T.; Steel, H.; Bert, W.; Maenhout, P.; Sleutel, S.; De Neve, S. Quantifying the contribution of entire free-living nematode communities to carbon mineralization under contrasting C and N availability. PLoS ONE 2015, 10, e01 36244.
22. Habteweld, A.W.; Brainard, D.C.; Kravchenko, A.N.; Grewal, P.S.; Melakeberhan, H. Effects of plant and animal waste-based compost amendments on soil food web, soil properties, and yield and quality of fresh market and processing car rot cultivars. Nematology 2018, 20, 147–168.
23. Helms, I.V.; Ijelu, J.A.; Willis, B.D.; Landis, D.A.; Haddad, N.M. Ant biodiversity and ecosystem services in bioenergy la ndscapes. Agr. Ecosyst. Environ. 2020, 290.
24. Toosi, E.R.; Kravchenko, A.N.; Guber, A.K.; Rivers, M.L. Pore characteristics regulate priming and fate of carbon from p lant residue. Soil Biol. Biochem. 2017, 113, 219–230.
25. The 4R Principles of Nutrient Management—Do You Really Know Them? Meister Media Worldwide: Willoughby, OH, U SA, 2021; Available online: (accessed on 10 March 2021).
26. Basso, B.G.; Zhang, S.J.; Robertson, G.P. Yield stability analysis reveals sources of large-scale nitrogen loss from the US Midwest. Nat. Sci. Rep. 2019, 10, 5774.
27. Kang, G.S.; Beri, V.; Sidhu, B.S.; Rupela, O.P. A new index to assess soil quality and sustainability of wheat-based crop ping systems. Biol. Fertil. Soils. 2005, 41, 389–398.
28. Melakeberhan, H. Fertiliser use efficiency of soybean cultivars infected with Meloidogyne incognita and Pratylenchus p enetrans. Nematology 2006, 8, 129–137.
29. Melakeberhan, H.; Avendaño, M.F. Spatio-temporal consideration of soil conditions and site-specific management of ne matodes. Precis. Agric. 2008, 9, 341–354.
30. Melakeberhan, H. Cross-disciplinary efficiency assessment of agronomic and soil amendment practices designed to su ppress biotic yield-limiting factors. J. Nematol. 2010, 42, 73–74.
31. Jangid, K.; Williams, M.A.; Franzluebbers, A.J.; Sanderlin, J.S.; Reeves, J.H.; Endale, M.B.; Coleman, D.C.; Whitman, W.B. Relative impacts of land-use, management intensity and fertilization upon soil microbial community structure in ag ricultural systems. Soil Biol. Biochem. 2008, 40, 2843–2853.
32. Schutter, M.E.; Sandeno, J.M.; Dick, R.P. Seasonal, soil type, and alternative management influences on microbial com munities of vegetable cropping systems. Biol. Fertil. Soils. 2001, 34, 397–410.
33. Glavatska, O.; Muller, K.; Boutenschoen, O.; Schmalwasser, A.; Kandeler, E.; Scheu, S.; Totsche, K.U.; Ruess, L. Dise ntangling the root- and detritus-based food chain in the micro-food webs of an arable soil by plant removal. PLoS ONE 2017, 13, e0180264.
34. Ferris, H.; Bongers, T.; de Goede, R.G.M. A framework for soil food web diagnostics: Extension of the nematode faunal analysis concept. Appl. Soil Ecol. 2001, 18, 13–29.
35. Bongers, T.; Ferris, H. Nematode community structure as a bioindicator in environmental monitoring. Trends Evol. Ecol. 1999, 14, 224–228.
36. Van der Hoogen, J.; Geisen, S.; Routh, D.; Ferris, H.; Traunspurger, W.; Wardle, D.A.; De Goede, R.G.; Adams, B.J.; A hmad, W.; Andriuzzi, W.S.; et al. Soil nematode abundance and functional group composition at a global scale. Nature 2019, 572, 194–198.

37. Yeates, G.W. Modification and qualification of the nematode maturity index. Pedobiologia 1995, 38, 97–101.

38. Yeates, G.W.; Bongers, T.; de Goede, R.G.M.; Freckman, D.W.; Georgieva, S.S. Feeding habits in soil nematode famili es and genera an outline for soil ecologists. J. Nematol. 1993, 25, 315–331.

39. Bongers, T.; Bongers, M. Functional diversity of nematodes. Appl. Soil Ecol. 1998, 10, 239–251.

40. Ferris, H.; Venette, R.C.; Scow, K.M. Soil management to enhance bacterivore and fungivore nematode populations an d their nitrogen mineralization function. Appl. Soil Ecol. 2004, 24, 19–35.

41. Grabau, Z.J.; Chen, S. Influence of long-term corn-soybean crop sequences on soil ecology as indicated by the nemat ode community. Appl. Soil Ecol. 2016, 100, 172–185.

42. Grabau, Z.J.; Maung, Z.T.Z.; Noyes, C.; Baas, D.; Werling, B.P.; Brainard, D.C.; Melakeberhan, H. Effects of cover crop s on Pratylenchus penetrans and the nematode community in carrot production. J. Nematol. 2017, 49, 114–123.

43. Kovacs-Hostyanszki, A.; Elek, Z.; Balazs, K.; Centeri, C.; Falusi, E.; Jeanneret, P.; Penksza, K.; Podmaniczky, L.; Szalk ovszki, O.; Baldi, A. Earthworms, spiders and bees as indicators of habitat quality and management in low-input farmin g region—A whole farm approach. Ecol. Indic. 2013, 33, 111–120.

44. Fixen, P.; Brentrup, F.; Bruulsema, T.W.; Garcia, F.; Norton, R.; Zingore, S. Nutrient/fertilizer use efficiency: Measureme nts, current situation and trends. In Managing Water and Fertilizer for Sustainable Agricultural Intensification, 1st ed.; D rechsel, P., Heffer, P., Magen, H., Mikkelsen, R., Wichelns, D., Eds.; International Fertilizer Industry Association, Interna tional Water Management Institute, International Plant Nutrition Institute, and International Potash Institute: Paris, Franc e, 2011; pp. 8–38. Available online: (accessed on 19 May 2021).

45. Melakeberhan, H. Effect of starter nitrogen on soybeans under Heterodera glycines infestation. Plant Soil. 2007, 301, 1 11–121.

46. Bulluck, L.R., III; Barker, K.R.; Ristaino, J.B. Influences of organic and synthetic soil fertility amendments on nematode t rophic groups and community dynamics under tomatoes. Appl. Soil Ecol. 2002, 21, 233–250.

47. Kravchenko, A.N.; Snapp, S.S.; Robertson, G.P. Field-scale experiments reveal persistent yield gaps in low-input and o rganic cropping systems. Proc. Natl. Acad. Sci. USA 2017, 114, 926–931.

48. Carrera, L.M.; Buyer, J.S.; Vinyard, B.; Abdul-Baki, A.A.; Sikora, L.J.; Teasdale, J.R. Effects of cover crops, compost an d manure amendments on soil microbial community structure in tomato production systems. Appl. Soil Ecol. 2007, 37, 247–255.

49. Melakeberhan, H.; Wang, W.; Kravchenko, A.; Thelen, K. Effects of agronomic practices on the timeline of Heterodera glycines establishment in a new location. Nematology 2015, 17, 705–713.

50. Miguez, F.E.; Bollero, G.A. Review of corn yield response under winter cover cropping systems using metadata analytic methods. Crop Sci. 2005, 45, 2318–2329.

51. Renco, M.; Gomoryova, E.; Cerevkova, A. The effect of soil type and ecosystems on the soil nematode and microbial c ommunities. Helminthologia 2020, 57, 129–144.

52. Ge, Z.W.; Brenneman, T.; Bonito, G.; Smith, M.E. Soil pH and mineral nutrients strongly influence truffles and other ect omycorrhizal fungi associated with commercial pecans (Carya illinoinensis). Plant Soil. 2017, 418, 493–505.

53. Bonito, G.; Reynolds, H.; Hodkinson, B.; Nelson, J.; Tuskan, G.; Robeson, M.; Schadt, C.; Vilgalys, R. Plant host and s oil origin influence fungal and bacterial assemblages in the rhizosphere of woody plants. Mol. Ecol. 2014, 23, 3356–33 70.

54. World Fertilizer Trends and Outlook to 2022; FAO: Rome, Italy, 2018; Available online: (accessed on 19 May 2021).

55. Adesemoye, A.O.; Kloepper, J.W. Plant-microbe interactions in enhanced fertilizer-use efficiency-Mini-review. Appl. Mic robio. Biotechnol. 2009, 85, 1–12.

56. Chagas, W.F.T.; Emrich, E.B.; Guelfi, D.R.; Caputo, A.L.C.; Faquin, V. Productive characteristics, nutrition and agronom ic efficiency of polymer-coated MAP in lettuce crops. Cienc. Agron. 2015, 46, 266–276.

57. Nissen, T.M.; Wander, M.M. Management and soil-quality effects on fertilizer-use efficiency and leaching. Soil Sci. Soc. Am. J. 2003, 67, 1524–1532.

58. Olk, D.C.; Cassman, K.G.; Simbaha, G.; Sta Cruz, P.C.; Abdulrachman, S.; Nagarajan, R.; Tan, P.S.; Satawathananon, S. Interpreting fertilizer-use efficiency in relation to soil nutrient-supplying capacity, factor productivity, and agronomic ef ficiency. Nutr. Cycl. Agroecosyst 1999, 53, 35–41.

59. Biesiada, A.; Koota, E. The Effect of nitrogen fertilization on yield and quality of Radicchio. J. Elementol. 2008, 13, 175–180.

60. Blanc, C.; Sy, M.; Djigal, D.; Brauman, A.; Normand, P.; Villenave, C. Nutrition on bacteria by bacterial-feeding nematodes and consequences on the structure of soil microbial community. Eur. J. Soil Biol. 2006, 42, S70S78.
61. Gibson, J.; Shokralla, S.; Porter, T.M.; King, I.; van Konynenburg, S.; Janzen, D.H.; Hallwachs, W.; Hajibabaei, M. Simultaneous assessment of the macrobiome and microbiome in a bulk sample of tropical arthropods through DNA metasystematics. Proc. Natl. Acad. Sci. USA 2014, 111, 8007–8012.
62. Riga, E.; Mojtahedi, H.; Ingham, R.E.; McGuire, A.M. Green manure amendments and management of root knot nematodes on potato in the Pacific Northwest of USA. Nematol. Monogr. Perspect. 2003, 2, 151–158.
63. Schorpp, Q.; Schrader, S. Earthworm functional groups respond to the perennial energy cropping system of the cup plant (Silphium perforliatum). Biomass Bioenergy 2016, 87, 61–68.
64. Toosi, E.R.; Kravchenko, A.N.; Quigley, M.M.; Mao, J.; Rivers, M.L. Effects of management and pore characteristics on organic matter composition of macroaggregates, evidence from X-ray µ-tomography, FTIR and 13C-NMR. Eur. J. Soil Sci. 2017, 68, 200–211.
65. van Leeuwen, J.P.; Djukic, I.; Bloem, J.; Lehtinen, T.; Hemerick, L.; de Ruiter, P.C.; Lair, G.J. Effects of land use on soil microbial biomass, activity and community structure at different soil depth in the Danube floodplain. Eur. J. Soil Biol. 2017, 79, 14–20.
66. Wang, K.H.; McSorley, R.; Kokalis-Burelle, N. Effects of cover cropping, solarization, and fumigation on nematode communities. Plant Soil. 2006, 286, 229–243.
67. Wang, K.H.; Radovich, T.; Pant, A.; Cheng, Z. Integration of cover crops and vermicompost tea for soil and plant health management in a short-term vegetable cropping system. Appl. Soil Ecol. 2014, 82, 26–37.
68. Wickings, K.; Grandy, A.S.; Kravchenko, A.N. Going with the flow: Landscape position drives differences in microbial biomass and activity in conventional, low input, and organic agricultural systems in the Midwestern, U.S. Agric. Ecosyst. Environ. 2016, 218, 1–10.
69. Xiao, H.; Li, G.; Li, D.-M.; Hu, F.; Li, H.-X. Effect of different bacterial feeding nematode species on soil bacterial numbers, activity and community composition. Pedosphere 2014, 24, 116–124.
70. Zhang, X.; Ferris, H.; Mitchell, J.; Liang, W. Ecosystem services of the soil food web after long-term application if agricultural management practices. Soil Biol. Biochem. 2017, 111, 36–43.
71. Emery, S.M.; Reid, M.L.; Bell-Dereske, L.; Gross, K.L. Soil mycorrhizal and nematode diversity vary in response to bioenergy crop identity and fertilization. Glob. Chang. Biol. Bioenergy 2017, 9, 1644–1656.
72. Kokalis-Burelle, N.; Mahaffee, W.F.; Rodriguez-Kabana, R.; Klopper, J.W.; Brown, K.L. Effects of switchgrass (Panicum virgatum) rotations with peanut (Arachis hypogaea L.) on nematode populations and soil microflora. J. Nematol. 2002, 34, 98–105.
73. Jian, J.; Du, X.; Stewart, R.D. A database for global soil health assessment. Nature. Sci. Data 2020, 7, 16.
74. Wander, M.M.; Cihacek, L.J.; Coyne, M.; Drijber, R.A.; Grossman, J.M.; Gutknecht, J.L.M.; Horwath, W.R.; Jagandamma, S.; Olk, D.C.; Ruark, M.; et al. Developments in agricultural soil quality and health: Reflections by the research committee on soil organic matter management. Front. Environ. Sci. 2019, 7, 1–9.
75. Fine, A.K.; van Es, H.M.; Schindelbeck, R.R. Statistics, Scoring Functions, and Regional Analysis of a Comprehensive Soil Health Database. Soil Sci. Soc. Am. J. 2017, 81, 589.
76. Kihara, J.; Bolo, P.; Kinyua, M.; Nyawira, S.S.; Sommer, R. Soil health and ecosystem services: Lessons from sub-Saharan Africa. Geoderma 2019, 370, 141342.
77. Stewart, Z.P.; Pierzynski, G.M.; Middendorf, B.J.; Prasad, P.V.V. Approaches to improve soil fertility in sub-Saharan Africa. J. Exp. Bot. 2020, 71, 632–641.
78. Liu, T.; Hu, F.; Li, H. Spatial ecology of soil nematodes: Perspectives from global to micro scales. Soil Biol. Biochem. 2019, 137, 107565.