19

Soil Biology Is Enhanced under Soil Conservation Management

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Soil biology embodies a stunning array of soil-inhabiting organisms ranging from viruses and microorganisms to macroinvertebrates and burrowing mammals, encompassing their activities and inter-organismal relationships, resulting in an environment with likely the most complex biological communities on earth. The "soil microbiome" is defined as the characteristic microbial community occupying specified microhabitats with distinct physio-chemical properties. The soil microbiome represents both taxonomic and functional diversity that is mediated by individual members as well as the overall community. This perspective provides a framework for describing and understanding how soil biological relationships interact with conservation management.

Historically, soil conservation goals focused on modification of land use and management practices to protect the soil resource against physical loss by erosion or chemical deterioration and loss of fertility. With recent scientific advancements, the emphasis of current efforts has shifted toward microbiome interactions with soil physical and chemical processes, and how this important soil biological component is also prone to degradation by poor management. The primary objectives of this chapter are to (1) consider detrimental land management effects on the soil microbiome and essential biological processes, and (2) consider how biological functioning of the soil microbiome can be improved through application of soil conservation practices to reverse soil

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degradation and improve soil health. In addition, this chapter will illustrate current research efforts to identify soil properties most affected by land use and management, especially those associated with soil organic matter (SOM) and the diversity of the soil microbiome, and how this knowledge is shaping our understanding of the interactions that drive biological activity and fueling interest in soil health assessment.

The Microbiome and Soil Health

Soil health is an evolving concept and may be defined as the capacity of a living soil to function within ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health (Doran 2002). Coleman et al. (1998) emphasized the role of the soil microbiome by asserting that the health and balanced activity of *all groups of organisms within an ecosystem* is implicit and should be specifically noted as a component of soil health. Lehman et al. (2015) affirmed the importance of microbial diversity and activity as the basis for soil function because critical environmental services are driven by diverse soil biological communities. Optimal soil health requires a balance between soil functions for productivity, environmental quality, and plant and animal health—all of which are greatly affected by management and land use decisions. Albrecht (1967) noted decades ago the relationship between healthy food quality and soil management practices that encourage healthy soil microbial communities and, hence, a healthy soil.

Historical Perspective

Soil biology as a principal concept in soil science was advanced in the early 20th century by Jacob Lipman and refined by Selman Waksman (1931), who described soils as complex systems sustaining microbial communities that influenced soil fertility and crop production. During the mid-20th century, Hans Jenny recognized the community of microorganisms as a critical component of the organism soil factor (one of the five soil forming factors) in his seminal book, *Factors of Soil Formation* (1941). He illustrated a scenario beginning with chemolithotrophic bacteria breaking down parent materials and releasing minerals; phototrophic bacteria and algae establishing on the developing soil matrix and forming organic matter; nitrogen accumulation by nitrogen-fixing bacteria; mycorrhizal fungi promoting plant growth and stabilizing the soil; and various meso- and macrofauna aiding soil structural development (Jenny 1980).

In the aftermath of the Dust Bowl (1935 to 1938), W.A. Albrecht, writing in the *1938 USDA Yearbook of Agriculture—Soils and Men*, proposed that soil degradation caused by intensive tillage and subsequent erosion led to depletion of SOM that exhausted the substrates required for soil microbial contributions to plant nutrition and soil structural stability. He emphasized the restoration of SOM through additions of green manure crops and livestock manures to stimulate soil microbial communities to release plant-available nutrients and to stabilize soil structure. This represents an early recognition of the importance of microbial ecology in soil conservation. Albrecht (1967) also indicated that plants as sources of fixed carbon (C) and microorganisms as decomposers and synthesizers of numerous organic compounds together create a dynamic living environment within a naturally conserved soil.

Early studies of SOM established that the soil organic carbon (SOC) pool supported biological activity, serving as the primary source of energy and nutrients for the soil microbiome, and that in turn the soil microbial community drove the process of SOM formation primarily via decomposition of organic substances entering the soil environment. The rate of decomposition was generally assumed to be constant; however, several intensive studies beginning around the mid-20th century recognized that the SOM pool consisted of a complex of recent inputs of easily metabolizable plant materials (labile or "young SOM"), a component of partially decomposed compounds of plant and microbial origin decaying at an intermediate rate, all of which were intermixed with resistant SOM decaying at very slow rates. Thus, decomposition of the diverse organic substances in soil was determined to follow first-order reaction processes rather than a zero rate or constant process (Jenkinson and Rayner 1977; Janssen 1984). Application of the revised decomposition principles to field studies showed that decay rates of labile SOM pools were strongly influenced by ecosystem differences (i.e., native prairie versus cultivated), such as soil disturbance, aeration, and moisture, establishing that conventional soil management resulted in SOM losses whereas no-till, which mimicked natural conditions, increased SOM content (Buyanovsky et al. 1987).

These early efforts formed our current understanding of the dynamics of decomposition and identification of SOC fractions and were important in future development of sensitive biological indicators of soil health for assessments of soil management. Examples of these soil health indicators currently in use include soil respiration, microbial biomass C, and the active C fraction of SOM (discussed below).

The importance of soil as the essential foundation for life on Earth and awareness that past degradation and erosion needed to be addressed through conservation management to restore the dynamic nature of soil garnered public attention in the latter quarter of the 20th century through popular outlets including the September of 1984 issue of *National Geographic*. This issue featured USDA Agricultural Research Service microbiologist Dr. John Doran describing his soil respiration measurements as useful indicators of biological activity that increased in a robust, healthy soil. The restoration of soils, including inherent, critical biological functions, continues to be a major concern today as their role in food, climate, and human security become more fully understood, as was featured in the highly regarded scientific journal *Science* (Amundson et al. 2015).

Soil Biology and Soil Conservation Practices

The impact of soil organisms in soil structure modification, long recognized by farmers and described by Jenny (1980), was first conceptualized for soil aggregation within the last 40 years (Barrios 2007). Soil aggregates, microbially induced through cementation and binding of soil particles by bacteria and fungi with microbial metabolites (i.e., extracellular polysaccharides or biofilms) and occluded SOM, and enmeshment with fungal hyphae, provide microhabitats for microbiomes, which mediate many functional activities. Stable aggregation ensures long-term subsistence of microbial habitats while disruption of unstable soil aggregates disperses SOM exposing it to mineralization and suppresses microbial activity. Conservation management practices promoting aggregate formation include no-till, residue retention, cover cropping, diversified and extended crop rotations, and organic amendments. These practices stimulate biofilm-producing bacteria and mycorrhizal fungi to improve aggregate stability and are based on studies that strongly correlate stability with active microbial biomass, microbial enzyme activity, SOM content, active C content, and mycorrhizal fungal abundance (Veum et al. 2015).

Further, soils under conservation management exhibit more abundant and active microbial biomass, lower specific respiration, and reduce environmental stress on the microbiome relative to conventional systems (Islam and Weil 2000). This was confirmed over a decade later by research showing that fungal-based soil food webs of grasslands were more resistant and more adaptive to drought relative to bacterial-based food webs in intensively managed wheat (de Vries et al. 2012). Using applied soil food web analyses, Coleman (2011) noted that complex, diverse soil food webs were highly functional under zero and conservation tillage and suggested conservation practices are an essential component of effective soil food web management. Recent developments in defining the quality of SOM through fractionation of pools of SOC allow realistic assessments of the effects soil degradation and soil conservation practices have on the ability of soil to retain C for supporting a diverse soil microbiome. The active C pool consists of easily decomposable organic substances that, along with very labile soluble C compounds mainly originating from plant root exudates, provide readily accessible substrates for the microbiome and mineralizable nutrients (Islam and Weil 2000). Active C from decomposing residues, including dead microbial biomass, also influences soil structural stability but is readily depleted if such organic additions are reduced or subjected to intensive tillage. The understanding of the active C pool as a SOC component may better predict effects of practices such as crop residue management illustrated by recent findings that "unharvestable C" sources, or labile C, of maize crowns, roots, and root exudates contribute nearly twice the amount of C to SOC than aboveground stover residue (Wilts et al. 2004). Thus, maize harvest practices (grain and stover) have implications for source C contributions into SOC and may guide in determining stover biomass amounts for bioenergy production (Wilts et al. 2004).

Many formative studies have demonstrated direct relationships between soil biological measurements and conservation management including microbial biomass, soil enzyme activities, active C, and phospholipid fatty acid (PLFA) microbial community profiles, which has led to the recommendation of these measurements as sensitive and informative indicators for soil health assessments (Islam and Weil 2000; Acosta-Martinez et al. 2003; Kennedy and Papendick 1995).

Future Developments for Conservation in Improving Soil Biology and Soil Function

Functional diversity and microbial activity play key roles in soil ecosystem dynamics, including resilience and stability, productivity, nutrient cycling, and other ecosystem services. Thus, microbial community structure may be relatively less important in soil health assessment than a knowledge and understanding of the functional attributes of the soil microbiome (Barrios 2007; Coleman 2011). However, techniques are constantly evolving, and our knowledge of and ability to interpret genetic information on the abundance and diversity of microbial species is rapidly expanding (Manter et al. 2017). Molecular techniques were effectively demonstrated in a regional study of microbial diversity in midwestern US tallgrass prairie soils by Fierer et al. (2013) who applied metagenomics to describe soil bacterial community abundance patterns and the relationship of taxonomic composition to functional gene categories (e.g., carbohydrate metabolism). This original study revealed previously unknown soil bacterial diversity and associated biological functions under the naturally conserved environments of the native prairie and also provided important information for reviving the soil microbiome for successful restoration or reconstruction of prairie ecosystems as a conservation practice. A more recent study using a high-throughput gene sequencing approach found that within the soils under long-term crop production (more than 52 years), crop rotation combined with no-till soil management yielded the highest bacterial diversity and functional capacity based on predicted gene abundances (Sengupta et al. 2020). Interestingly, a legacy effect from conversion of the original forested sites to agricultural fields was apparent in lost soil microbial functional potential. Overall, application of modern molecular techniques to assess soil microbiome composition and function provides critical information on the impact of agricultural land management and may become a valuable tool in assessing soil health.

Characterization of the soil microbiome directly in the field for real-time assessment of soil health and conservation management impacts using field-based genomics diagnostic tools will become a reality in the near future. Genes coding for the various processes, or functions, mediated by the soil microbiome will also be assessed using diagnostic tools and thereby aid in measuring the dynamics of soil functions, or the changes induced by management, which will lead to development of practices to improve soil health (Vogel et al. 2018). Ultimately the use of diagnostic tests to directly evaluate soil functional dynamics in response to disruption or degradation due to inadequate management will effectively identify research needs for a better understanding of the overall behavior of soil systems, their stability, and resilience (Vogel et al. 2018). Recent work with portable, small-scale DNA sequence platforms and new DNA enrichment methods results in identification of hundreds of bacterial identifications in food in less than two hours and will be potentially expressed as real-time data collection (Krych et al. 2019). This diagnostic approach is expected to become a modern standard molecular-based method with applications in many life science disciplines, including agriculture (Krych et al. 2019).

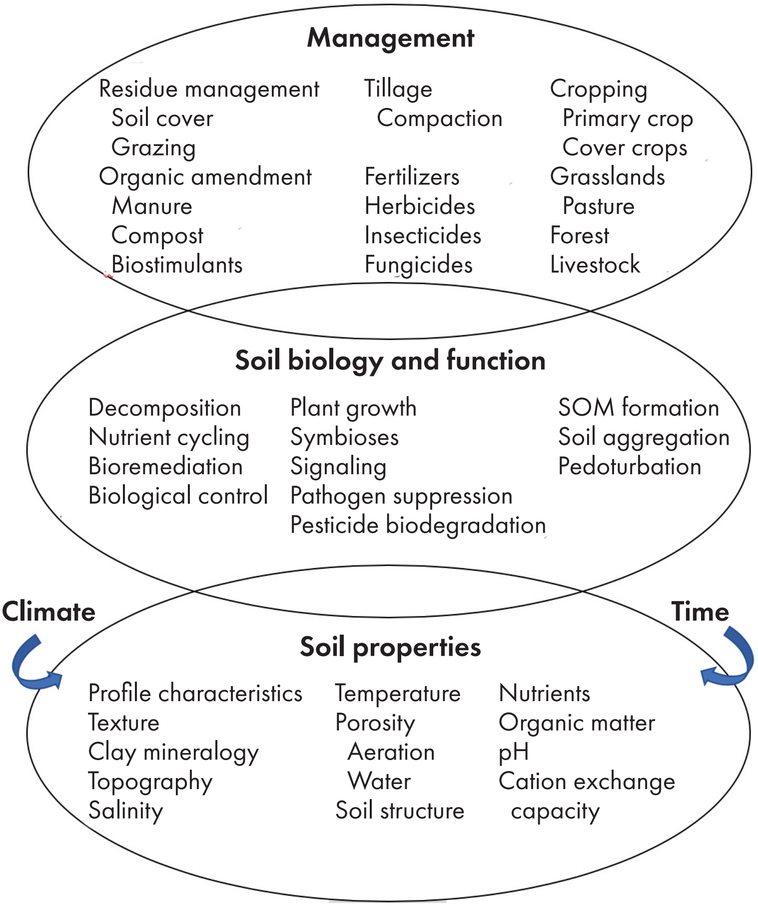
In addition, recent advances with in situ sensor technology outside the laboratory under farmers' field conditions are providing rapid, high-resolution data collection opportunities for soil health assessment (Veum et al. 2017, 2018). These tools, along with novel statistical approaches, offer the potential for real-time data collection with an environmentally relevant interpretation. Ultimately, taxonomic soil biodiversity paired with knowledge of microbial function and activity using laboratory or field techniques can provide a wealth of information on biological processes affected by conservation practices.

Conclusions

Understanding soil biology in terms of structural and functional diversity suggests that management of the soil microbiome can lead to preservation of our soil resource and sustainably increase agricultural productivity. Taxonomic soil biodiversity paired with knowledge of microbial function and

Figure 1

Conservation management practices and soil properties influence soil biology and function through simultaneous interactions within an ecosystem. Modified from Kennedy and Papendick (1995).



activity provide a wealth of information on biological processes affected by conservation practices. Previous reviews established the link between management impacts on soil physical and chemical properties and subsequent changes in soil biology and function (figure 1 [Kennedy and Papendick 1995]). The current resurgence in the use of cover cropping, no-till, extended rotations, livestock integration, biostimulants, and organic amendments aid in management of the soil microbiome to promote soil biological activity and productivity. Advancements in development of tools and techniques for assessment of soil microbiome structure and function and other soil health indicators will guide future conservation management decisions that will ultimately lead to more resilient agriculture, a more stable food security, and improved environmental outcomes.

References

Acosta-Martínez, V., S. Klose, and T.M. Zobeck. 2003. Enzyme activities in semiarid soils under conservation reserve program, native rangeland, and cropland. Journal of Plant Nutrition and Soil Science 166(6):699-707.

Albrecht, W.A. 1938. Loss of soil organic matter and its restoration. *In* Soils and Men. USDA Yearbook of Agriculture. Washington, DC: US Government Printing Office.

Albrecht, W.A. 1967. Problems of quality in the productivity of agricultural land. *In* Natural Resources: Quality and Quantity, eds. S.V. Ciriacy-Wantrup, and J.J. Parsons, 55-70. Berkeley, CA: University of California Press.

Amundson, R., A.A. Berhe, J.W., Hopmans, C. Olson, A.E. Sztein, and D.L. Sparks. Soil and human security in the 21st century. Science 348(6235):647, doi:10.1126/science.1261071.

Barrios, E. 2007. Soil biota, ecosystem services and land productivity. Ecological Economics 64(2):269-285.

Buyanovsky, G.A., C.L. Kucera, and G.H. Wagner. 1987. Comparative analyses of carbon dynamics in native and cultivated ecosystems. Ecology 68(6):2023-2031.

Coleman, C.C., P.F. Hendrix, and E.P. Odum. 1998. Ecosystem health: An overview. *In* Soil Chemistry and Ecosystem Health, ed. P.H. Wang, 1-20. Special Publication No. 52. Madison, WI: Soil Science Society of America.

Coleman, D.C. 2011. Understanding soil processes: One of the last frontiers in biological and ecological research. Australasian Plant Pathology 40(3):207-214.

Doran, J.W. 2002. Soil health and global sustainability: Translating science into practice. Agriculture, Ecosystems and Environment 88(2):119–127.

Fierer, N., J. Ladau, J.C. Clemente, J.W. Leff, S.M. Owens, K.S. Pollard, R. Knight, J.A. Gilbert, and R.L. McCulley. 2013. Reconstructing the microbial diversity and function of pre-agricultural tallgrass prairie soils in the United States. Science 342(6158):621-624.

Islam, K.R., and R.R. Weil. 2000. Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management. Journal of Soil and Water Conservation 55(1):69-78.

Janssen, B.H. 1984. A simple method for calculating decomposition and accumulation of ‘young’ soil organic matter. Plant and Soil 76(1-3):297-304.

Jenkinson, D.S., and J.H. Rayner. 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Science 123(5):298-305.

Jenny, H. 1941. Factors of Soil Formation. New York: McGraw-Hill.

Jenny, H. 1980. The Soil Resource – Origins and Behavior. Ecological Studies, Vol. 37. New York: Springer-Verlag.

Kennedy, A.C., and R.I. Papendick. 1995. Microbial characteristics of soil quality. Journal of Soil and Water Conservation 50(3):243-248.

Krych, Ł., J.L. Castro-Mejía, L.M. Forero-Junco, D.N. Moesby, M.B. Mikkelsen, M.A. Rasmussen, M. Sykulski, and D.S. Nielsen. 2019. DNA enrichment and tagmentation method for species-level identification and strain-level differentiation using ON-rep-seq. Communications Biology 2:369, doi:10.1038/s42003-019-0617-x.

Lehman, R.M., V. Acosta-Martínez, J.S. Buyer, C.A. Cambardella, H.P. Collins, T.F. Ducey, J.J. Halvorson, V.L. Jin, J.M.F. Johnson, R.J. Kremer, J.G. Lundgren, D.K. Manter, J.E. Maul, J.L. Smith, and D.E. Stott. 2015. Soil biology for resilient, healthy soil. Journal of Soil and Water Conservation 70(1):12A-18A, doi:10.2489/jswc.70.1.12A.

Manter, D.K., J.A. Delgado, H.D. Blackburn, D. Harmel, A.A. Pérez de León, and C.W. Honeycutt. 2017. Opinion: Why we need a National Living Soil Repository. Proceedings of the National Academy of Sciences 114(52):13587-13590.

Sengupta, A., J. Hariharan, P.S. Grewal, and W.A. Dick. 2020. Bacterial community dissimilarity in soils is driven by long-term land-use practices. Agrosystems, Geosciences and Environment 3:e20031, doi.org/10.1002/agg2.20031.

Veum, K.S., R.J. Kremer, K.A. Sudduth, N.R. Kitchen, R.N. Lerch, C. Baffaut, D.E. Stott, D.L. Karlen, and E.J. Sadler. 2015. Conservation effects on soil quality indicators in the Missouri Salt River Basin. Journal of Soil and Water Conservation 70(4):232-246. https://doi.org/10.2489/jswc.70.4.232.

Veum, K.S., P.A. Parker, K.A. Sudduth, and S.H. Holan. 2018. Predicting profile soil properties with reflectance spectra via Bayesian covariate assisted external parameter orthogonalization. Sensors 18(11):3869.

Veum, K.S., K.A. Sudduth, R.J. Kremer, and N.R. Kitchen. 2017. Sensor data fusion for soil health assessment. Geoderma 305(1):53-61.

Vogel, H.-J., S. Bartke , K. Daedlow , K. Helming, I. Kögel-Knabner, B. Lang, E. Rabot, D. Russell, B. Stößel, U. Weller, M. Wiesmeier, and U. Wollschläger. 2018. A systemic approach for modeling soil functions. Soil 4(1):83-92.

de Vries, F.T., M.E. Liiri, L. Bjørnlund, M.A. Bowker, S. Christensen, H.M. Setälä, and R.D. Bardgett. 2012. Land use alters the resistance and resilience of soil food webs to drought. Nature Climate Change 2(4):276-280.

Waksman, S.A. 1931. Principles of Soil Microbiology. London: Tindall & Cox.

Wilts, A.R., D.C. Reicosky, R.R. Allmaras, and C.E. Clapp. 2004. Long-term corn residue effects: Harvest alternatives, soil carbon turnover, and root-derived carbon. Soil Science Society of America Journal 68(4):1342-1351.