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Soil Health: Evolution, Assessment, and Future Opportunities

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Seventy-five years have passed since the Soil and Water Conservation Society (SWCS), initially the Soil Conservation Society of America, was formed to advance the science and art of good land and water use. Many scientists and engineers have contributed to the SWCS mission and have planted seeds for current soil health endeavors. I define soil health holistically, reflecting soil biological, chemical, and physical property and process interactions, in response to inherent and/or anthropogenic forces. To some, soil health is a new concept, but I suggest it evolved slowly, reflecting SWCS endeavors like soil condition, soil management, soil protection, and soil quality. Recently soil health has been integrated not only into scientific and technical writings, but also in news articles, community discussions, and sustainability platforms of several large consumer-product companies. Focusing on soil health will improve soil management and decision making, and increase support for sustaining our fragile natural resources, including water quality and quantity, while simultaneously meeting increasing global food, feed, fiber, and fuel demand. Emerging developments in genomics and molecular-based characterization of the microbial community are beginning to unlock secrets of total soil organic matter (SOM). This knowledge, plus SWCS conservation advancements, provides an accomplishment truly worthy of celebration.

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Evolution of the Soil Health Concept

Soil health has become embedded in global technical and nontechnical writings during the first two decades of the 21st century. Some may regard the concept as new and unique, but I suggest the scientists, engineers, producers, conservationists, and policy makers who sustained the SWCS were the leaders who helped build better public awareness and concern for our fragile soil resources through what is now known and accepted as soil health. By defining soil health holistically, I envision that a combination of soil/water conservation and management efforts (i.e., water-, wind-, and tillage-induced soil erosion studies; concepts such as soil condition, tilth, productivity, quality, care, resilience, security, and degradation; and air or water assessments) have now made soil health a driver encouraging producers to recognize and adopt better soil and water conservation practices. Federal and state government, nongovernment organizations, foundations, institutes, college and university curricula, public-private partnerships, and numerous other entities have all embraced the soil health concept and thus embedded the term into the vernacular of many groups around the world. For those who have spent recent decades striving to encourage adoption of soil health principles, especially the US Department of Agriculture Natural Resources Conservation Service (USDA NRCS; see Chapter 21 by Fisher), global recognition and acceptance of soil health is gratifying, but I am confident that all who have contributed to soil health endeavors fully acknowledge our small and humble contributions were built on foundations provided by the SWCS and many others before us.

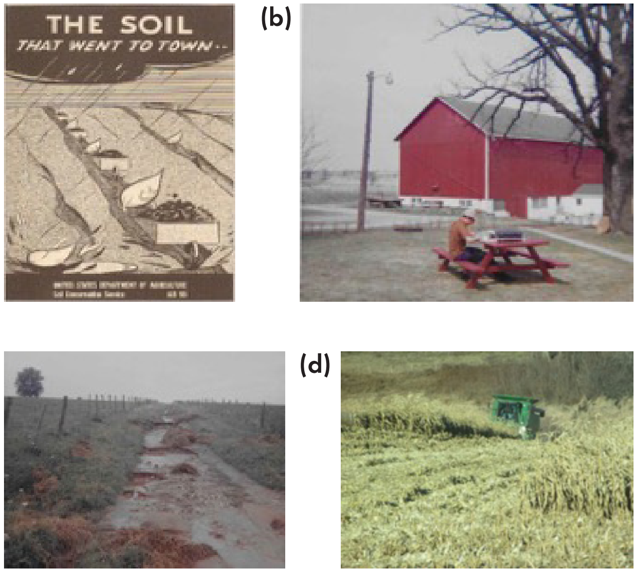
Having been significantly influenced by the SWCS throughout my career, I chose to personalize this chapter. My soil health journey was inspired by the SWCS and similar organizations who disseminated materials communicating soil and water conservation goals, not only to adults but also youth. As shown in figure 1, a USDA Soil Conservation Service (SCS) middle-school reading project (figure 1a), coupled with 4-H projects (figure 1b) examining on-farm soil erosion (figure 1c), ultimately led to a research career that provided many national and international opportunities to advocate for better conservation. This evolved into soil health and sustainable agriculture studies that included identifying inappropriate land use decisions that were unintentionally supported by crop insurance on land so steep a combine could barely climb the hill (figure 1d).

I credit the SWCS for the conservation inspiration that developed and sustained environmental awareness. My interest in science, coupled with a love for agriculture, led first to a bachelor's degree in soil science, followed by graduate research on soil fertility, plant nutrition, and water management interactions. Collectively, those events provided the foundation for my vision

Figure 1

A personal collage reflecting my inspiration and perception of soil health.

(a) (b) (c) (d)



of soil health, which was further reinforced by SWCS leaders such as W.E. (Bill) Larson, who often described soil as "the thin layer covering the planet that stands between us and starvation" (Karlen et al. 2014a). Bill's quote parallels inspirational writings by two other soil conservation leaders whom I credit for indirectly helping formulate the soil health concept. The first is W.C. Lowdermilk (1953) who summarized his personal experiences in 1938 and 1939 in an often-reproduced publication entitled *Conquest of the Land through 7,000 Years*. This writing emphasized that human civilizations literally write their records on the land. Parallel to current soil health actions, Lowdermilk used his experiences to increase public awareness of soil erosion problems within the United States and around the world. I was also inspired by another influential soil scientist, Daniel Hillel (1991), who in his book, *Out of the Earth: Civilization and the Life of the Soil*, included a treatise that he states Plato had Critias proclaim:

> What now remains of the formerly rich land is like the skeleton of a sick man, with all the fat and soft earth having wasted away and only the bare framework remaining. Formerly, many of the mountains were arable. The plains that were full of rich soil are now marshes. Hills that were once covered with forests and produced abundant pasture now produce only

food for bees. Once the land was enriched by yearly rains, which were not lost as they are now, by flowing from the bare land into the sea. The soil was deep, it absorbed and kept the water in the loamy soil, and the water that soaked into the hills fed springs and running streams everywhere. Now the abandoned shrines at spots where formerly there were springs attest that our description of the land is true.

Those inspirational writings, my small-farm roots, a love for diverse rural landscapes, and an admiration for conservationists like Hugh Hammond Bennett, as well as leaders such as Franklin Delano Roosevelt, who stated, "A nation that destroys its soils, destroys itself," were guiding principles that kept me focused on the SWCS goals of advancing the science and art of good land and water use for more than 40 years (figure 2). As a result, I connect soil health to "good land and water use" through a holistic definition of the concept that emphasizes interactions among soil biological, chemical, and physical properties and processes. Decisions regarding how we use or manage our fragile soil resources directly or indirectly influence water relations such as ponding, runoff, leaching, and availability to support plant growth and development. I also argue that neither soil health nor the SWCS mission should be considered new! Several years before the SWCS was formed, Keen (1931) wrote that the first recorded experiment on soil tilth (a precursor to soil quality and soil health endeavors) was published in a 1523 book entitled *Boke of Husbandry* by

Figure 2

The author's (a) small-farm roots in Wisconsin and (b) the beauty of diverse rural landscapes led to (c) a soil and plant management career and (d) international opportunities to promote soil health.

Fitzherbert. When describing how to sow peas and beans, Fitzherbert stated that the soil was not ready to be planted "if it synge or crye, or make any noise under thy fete" whereas "if it make no noyse and wyll beare thy horses, thane sowe in the name of God." Similarly, in a discussion about soils and their properties, Fream (1890) included the 17th-century quote, "Good tilth brings seeds, ill tilture weeds," which he attributed to Thomas Tusser.

As terminology for advancing the science and art of good land and water use evolved from soil tilth to soil quality to soil health, Karlen et al. (1990) reviewed several publications from the first seven decades of the 20th century. Those studies focused on soil tilth, structure, erosion, organic matter, tillage, crop rotation, and fertilizer management, and thus influenced evolution of my soil health perspectives. One of the most influential studies that laid groundwork for soil physical health was work by Yoder (1937). He concluded poor soil structure was a major problem because of its influence on granulation processes (aggregation); wetting, drying, freezing, and thawing cycles; organic matter accumulation and decomposition rates; biological activities; and plant root development, as well as tillage and crop rotation response. This was important for development of soil health assessments because it ultimately led to development of the "Yoder" water stable aggregate method that is currently being used for many assessment projects being led by the Soil Health Institute (SHI), Soil Health Partnership (SHP), and NRCS Soil Health Division (NRCS SHD). Wilson and Browning (1945) also emphasized soil aggregation and documented significant differences due to crop rotation. The importance of SOM and total nitrogen was documented by Whiteside and Smith (1941) as well as van Bavel and Schaller (1950). They and many others showed that soil erosion and crop rotation significantly affected SOM. They also concluded that gradual changes in soil productivity because of crop production and differences in the ability of crops to preserve, amend, or deplete soil resources have been documented since the beginning of agriculture.

It's not possible to fully acknowledge all of the research, laws, policies, or leaders in soil and water conservation that contributed to the scientific foundation upon which soil health has evolved. However, some key pioneers were Martin Alexander, Francis E. Allison, Hugh Hammond Bennett, Orville W. Bidwell, Francis D. Hole, Edward Hyams, Hans Jenny, Aldo Leopold, Thomas L. Lyon, Eldor A. Paul, Jerome I. Rodale, Robert S. Whitney, and Daniel H. Yaalon. Collectively, they improved our knowledge and understanding of how SOM, fertilizer, crop rotation, and tillage influenced numerous soil functions. Those studies provided the foundation for today's soil health movement, but the focus for most post-World War II studies was on soil physical and chemical properties and processes (i.e., soil chemical and physical health). This occurred, not because the importance of soil biology was being overlooked (Lyon et al. 1950), but due to very rapid advancements in machinery, fertilizer, weed, and insect control technologies. With regard to soil biology, Selma Waksman (known for discovering streptomycin) quantified SOM and nitrogen cycling by characterizing microbial decomposition of various plant components (Waksman and Hutchings 1935). He and colleagues also improved our understanding of how soil aggregates formed and were connected to microbial decomposition processes (Martin and Wakasman 1939, 1941). Those were important studies, but several decades passed before key biological advancements (e.g., understanding of DNA and development of modern instrumentation and methods of analysis) occurred. Thus, holistic soil health assessments were not feasible until soil biological, chemical, and physical health indicators could be combined and analyzed holistically.

Soil Health Assessment

During the 1970s and 1980s, soil erosion and productivity (Pierce et al. 1983, 1984), as well as water quality and nonpoint pollution, were recognized as critical soil and water conservation issues. Protection of wetlands through USDA SCS participation in the Water Bank program and the need to provide incentives to landowners to protect wetland habitat, as well as increased authority to monitor and assess the nation's natural resource base through the National Resources Inventory began to create a need and focal point for future soil quality/soil health assessment studies. I argue that the same principles of soil and water management that influence erosion, productivity, runoff, leaching, or nutrient cycling are exactly the same as those that affect soil health. For example, during the mid-1970s, an increasing awareness that decreased use of crop rotations, increased size and weight of farm tractors and implements, as well as increased use of conservation tillage practices were having measurable soil tilth impacts began to spread throughout the northern Corn Belt (Voorhees 1979). I believe this research was also a precursor to what has become holistic soil health investigations.

Prior to the evolution of soil health assessment, the primary data evaluation techniques used to evaluate erosion control, soil fertility or tillage treatments, and other management practices were single factor (reductionist) analysis of variance (ANOVA) and/or multivariate regression analyses with a limited number of independent soil physical, chemical, and perhaps SOM measurements. Those studies provided information, but complexity associated with the emerging problems began to emphasize that soils were being called upon to simultaneously address multiple functions (i.e., food and fiber production, recreation, and recycling or assimilation of wastes or other by-products). This led Warkentin and Fletcher (1977) to introduce the concept of soil quality (soil health), which emphasized that (1) soil resources are constantly being evaluated for many different uses; (2) multiple stakeholder groups are concerned about soil resources; (3) society's priorities and demands on soil resources are changing; and (4) soil resource and land use decisions are made in a human or institutional context. Another soil and crop management challenge influencing SOM, erosion, and crop productivity during the 1980s was the suggested harvest of crop residues for off-site bioenergy generation (Karlen et al. 1984). Soil erosion and productivity questions associated with crop residue removal ultimately led to one of the first soil quality (soil health) studies, which focused on field experiments in southwestern Wisconsin where crop residues had been removed, doubled, or retained for 10 years (Karlen et al. 1994a) using no-tillage, chisel plow, or moldboard plow practices (Karlen et al. 1994b). Those two publications introduced an assessment framework that with major refinement became known as the Soil Management Assessment Framework (SMAF) (Andrews et al. 2004).

The exponential growth in soil health assessment during the past two decades is simply too broad to be thoroughly reviewed here. As expected, there are proponents and opponents of using either SMAF or the Comprehensive Assessment of Soil Health (CASH) to assess soil health. Nonetheless, as those tools continue to be improved and used to combine soil biological, chemical, and physical data into component or overall soil health indices, our integrated assessment of soil health will improve. With regard to SMAF, per se, the number of indicators it can accommodate has been expanded since its release in 2004 (Wienhold et al. 2009; Stott et al. 2010). SMAF has been used to effectively assess soil management scenarios in the United States (Stott et al. 2011; Karlen et al. 2014b; Veum et al. 2015b; Zobeck et al. 2015; Hammac et al. 2016; Ippolito et al. 2017), Spain (Fernandez-Ugale et al. 2009; Imaz et al. 2010; Apesteguía et al. 2017), and Brazil (Cherubin et al. 2016a, 2016b, 2016c). Furthermore, having contributed to the development of CASH, developers of the two tools continue to collaborate (Moebius-Clune et al. 2016; van Es and Karlen 2019) for the advancement of soil health assessment. For those interested in more detail regarding past, current, and future soil health uses, methods, and goals, please see the forthcoming two-volume Soil Science Society of America and Wiley International book series entitled *Approaches to Soil Health Analysis* and *Laboratory Methods for Soil Health Assessment* (Karlen et al. 2021).

Scientific Advances Needed to Further Develop and Implement Soil Health Concepts

Research opportunities for science-based advancement of soil health assessment were recently reviewed by Karlen et al. (2019). Exponential growth in public interest and private support through the SHI, SHP, NRCS SHD, Foundation for Food and Agricultural Research (FFAR), and sustainability programs led by consumer-faced businesses, such as Walmart and Target, are providing new funding sources for many of those endeavors. This includes development of new tools and analytical techniques to improve soil and crop management. Those actions support my perception that holistic soil health activities are indeed helping to fulfill the SWCS mission of advancing the science and art of good land and water use. Therefore, I argue that improving soil health has emerged as one of the most effective conservation strategies for mitigating or even halting the global soil degradation that continues to occur through soil erosion, loss of SOM, and impaired water quality and quantities (Karlen and Rice 2015; Pandit et al. 2020).

Some infer that soil health is strictly an enhancement of soil biology. I disagree, although because of historical advances in soil chemical and physical properties and processes, new investments will likely have the greatest impact if focused on (1) improving our understanding of soil biology; (2) developing better in-field and remote-sensing data collection techniques; and (3) interpreting soil biological, chemical, and physical data more holistically. Techniques to help develop a better understanding of the soil microbial community include genomics and other molecular markers, such as phospholipid fatty acids, which are being actively pursued to ensure agricultural sustainability and optimization of all ecosystem services (Lehman et al. 2015). Research focused on the using soil enzyme activities to characterize soil microbial communities and provide soil biochemical health indices (Acosta-Martinez and Harmel 2006; Acosta-Martinez et al. 2017; Cano et al. 2018) should also be expanded. CASH and SMAF, too, should be expanded and improved using new and innovative data assessment techniques. Advancements in sampling and monitoring of soil health indicators are needed, perhaps by development and use of low-cost, in situ soil sensors (Karlen et al. 2019). This includes development of visible-near-infrared techniques to quantify soil organic carbon, total nitrogen, β-glucosidase activity, active carbon, microbial biomass carbon, particulate organic matter carbon, and soil respiration (Pietikäinen and Fritze 1995; Chang et al. 2001; Vasques et al. 2009; Kinoshita et al. 2012; Veum et al. 2015a; Cho et al. 2017). Sensors could also be used quantify apparent electroconductivity throughout the soil profile since those measurements can then be used to assess soil texture, mineralogy, cation exchange capacity, and water content simply by using different calibration techniques. Vertical penetrometers or mobile, horizontal sensors should continue to be improved so that penetration resistance (Sudduth et al. 2008; Hemmat and Adamchuk 2008) can be measured and used provide information on compaction and soil bulk density. Finally, these types of measured, in situ, and/or remote-sensed data should be combined and used to improve overall SMAF scores as well as individual chemical, biological, and physical soil health scores as already shown by Veum et al. (2017).

Summary

This soil health overview commemorates the 75th anniversary of the SWCS. It also reflects my perception of the science that helped advance the concept exponentially during the past two decades. In contrast to more technical publications, I've included my personal experiences to reflect how the SWCS helped advance a career focused on the science and art of sustainable land, water, and crop management, integrated by the concept of soil health.

My perspective is that to provide meaningful and effective guidance for advancing soil and water conservation practices, science-based soil biological, chemical, and physical data must be collected, vetted, analyzed, and interpreted. Using a holistic soil health concept, assessment tools, such as the SMAF or CASH frameworks, will help meet those needs, but evolution of the concept is not finished. New and better techniques for measurement, data collection, and interpretation must continue to be developed. Understanding interactions among soil chemical and physical properties, biological communities, the environment, and human decision-making processes is essential to truly accomplish the SWCS mission.

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This article was written from a personal perspective that could only have evolved because of the inspiration and abundant support I received from my mentors, colleagues, and technical personnel throughout my career. There are too many to name individually, but to all, please accept my heartfelt thanks and gratitude for everything you have done to help protect "the thin layer covering the planet that stands between us and starvation."

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