SOIL HEALTH AND PRODUCTIVITY

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Summary

Soils represent dynamic ecosystems, making it appropriate to think about them in terms such as health, vitality and bioproductivity. Soils are the resources that provide humans with more than 90% of all the food we eat. Our challenge is to manage soils in a sustainable fashion so that they will provide for human needs in the future. However, the measurement of soil processes and of the soil properties linked to these also depend on the use and location of the soil. When evaluating soil health, it is therefore common to explore a range of soil physical, chemical, and biological properties.

The single most important property determining the health of the soil is the soil organic system because of the profound influence it has on soil physical, chemical, and biological properties. Therefore, many steps taken to improve soil health deal with improving soil organic matter status and hence the vitality of the soil organic system. Some of the common ways to improve soil health include: reduced tillage, use of green manure, application of animal manures, crop rotations, strip cropping, use of cover crops, application of sludge or biosolids, and other additions of organic materials and nutrients. These management techniques enhance the activity of both the micro- and macro-biological soil organic system, whose activities also improve properties such as soil aggregation, infiltration, and water holding capacity, decrease bulk density, penetration resistance and soil erosion, and increase cation exchange capacity.

Management for soil health can also lead to reduced need for agrochemicals and tillage, reduced fuel consumption by farm equipment, and increased sequestration of carbon dioxide in the soil, all of which benefit the environment. Modern agricultural science has the ability to correct many of the poor practices of the past and to maintain healthier soils that should sustain the uses they are put to.

1. Introduction

Soils are dynamic ecosystems that support a diversity of life. Therefore, the concept of soil health, like that of human health, is not difficult to understand or recognize when the system is viewed as a whole. The challenge is to manage soils such that they are able to perform the various uses they are put to without degradation of the soils themselves or the environment. While this is simple in concept, there are definite complexities that make the idea of soil health difficult to quantify. Which soil functions should be considered, which soil properties are most important to measure, and how to best measure those properties are some of the tough questions that need to be considered when attempting to quantify soil health.

1.1. Definition of Soil Health

Doran and Parkin (in Doran *et al.*, 1994) defined soil quality (health) as “the capacity of a soil to function, within ecosystem and land use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant and animal health.” It is worth noting here that “soil health” and “soil quality” are essentially synonymous terms.

At this point it is appropriate to dissect the soil health definition and look at each of its individual components. First, “the capacity of a soil to function…”. There are a number of “functions” carried out by the soil. For example, soil is a medium for the growth of plants and animals, a place where gases are exchanged, where water and energy moves, and where pollution can be neutralized. How well the soil can perform these tasks relates to its “capacity to function”.

The second part of the soil health definition says “…within ecosystem and land use boundaries…”. Soils function differently within different ecosystems and land uses. Therefore, the capacity of the soil to function is not the same everywhere. It is dependant upon the surrounding ecosystem and the use the soil is put to. Examples of different potential land uses include urban, agricultural cropland, pasture, or native systems such as prairie, forest, or wetlands (Figure 1). “Normal” soil function in an urban setting would be different than “normal” function in an agricultural setting, and both would be different than “normal” function in a wetland, for example.

Figure 1. Concepts of soil health and productivity can change with different land uses. Urban (left), production agriculture (left middle), rangeland (right middle), and wetlands (right) represent four common potential land uses**.** (Photo by Sarah Minor, USDA NRCS; photo courtesy of USDA NRCS; photo by Ron Nichols, USDA NRCS; photo by Eric Brevik)

The third part of the definition states “…to sustain biological productivity…”. The soil is a major ecological setting within which organisms thrive. More species probably exist below the soil surface than above it. How well a soil is performing its function as a “household” for soil organisms, and therefore sustaining biological productivity, is a major component of soil health.

Next, the definition says “…maintain environmental quality…”. Soils serve as a natural filter. As long as they are not overwhelmed with excessive amounts of pollutants, they can remove many harmful pollutants from soil water before it reaches the ground water or moves into rivers and streams, and can remove carbon dioxide from the atmosphere as a part of the soil-plant system. Through their pollution filtering effects, healthy soils help to maintain environmental quality.

Finally, the soil health definition states “…and promote plant and animal health.”. Healthy plants require soils with an appropriate balance of nutrients in which to grow, healthy herbivores require plants with an appropriate balance of nutrients on which to graze, and healthy carnivores require herbivores with an appropriate balance of nutrients they can eat. Ultimately, the health of all land organisms is tied to the soil. Therefore, healthy soils are required for healthy plants and animals all the way up the food chain, including healthy humans.

1.2. Concepts of Soil Health and Productivity

Because there are many different uses of soil, there are also many different concepts of what constitutes soil health. Probably the most familiar concept of soil health would be as it relates to the growth of plants. Soils with appropriate properties are important to grow abundant crops of corn, wheat, rice, and other crops that form the centerpiece of much of the world's diet.

A home gardener would have a very similar view of soil health as a farmer, as the home gardener would be interested in soils with appropriate properties to grow good crops of garden staples such as carrots, lettuce, peas, beans, potatoes, and so on. In the case of both the farmer and the home gardener, good soils are often associated with dark colored soils, because dark colored soils usually have high organic matter content. Such soils are often good soils to grow crops in because they contain a good mix of physical and chemical properties that support plant growth.

Another view of soil health involves nutrient availability. Consider, for example, soils used for two different cropping purposes. On one soil, the crop is blueberries (*Vaccinium corymbosum*). On another soil, the crop is corn (*Zea mays*). Blueberries thrive in acidic soils, while corn will struggle. This is because blueberries have a high iron requirement, and iron is readily available in acidic soils. These acidic soils are commonly lower in organic matter content and lighter in color than more basic soils that have the dark color often associated with fertility, but they may be well suited to supporting blueberries.

An engineer might have a very different idea of soil health altogether than a farmer or gardener. An engineer might, for example, be looking for a soil that will do a good job as a filtering material for a septic system. Soils that are good for the growth of crops may or may not be good for septic systems, as water table levels that are beneficial for the growth of crops might be too high for good septic performance. Soils used as a foundation for buildings are an entirely different issue again, as they will be too compact for a septic system or for good crop growth.

These brief examples are hardly comprehensive, in either the depth at which they are explored here or in illustrating all the different concepts of soil health that are out there. However, they do serve to illustrate that soil health is not a one size fits all proposition, and that is the main point to this particular discussion. Soil health means different things to different people, so there is no perfect set of properties that come together to describe a "healthy" soil. The concept of soil health is location and land use dependant.

Soil productivity can be defined as the capacity of a soil, in its normal environment, to support plant growth. In agricultural systems this relates directly to crop and forage yields, and ties directly back to the portion of the soil health definition that states "the capacity of a soil to…sustain biological productivity" (Doran and Parkin, in Doran *et al.,* 1994). Because one of the primary components of soil health is the provision of a soil environment that supports biological productivity, we find that soil productivity is directly linked to the concept of soil health.

1.3. Properties Important in Soil Health

Even though the properties that constitute a healthy soil are not the same in all places and all situations, there are some important soil properties that indicate soil health. These properties fall into three main categories: soil chemical properties, soil physical properties, and soil biological properties. Soil chemical and physical properties have long been studied by soil scientists, and the basic tests and their procedures are well established. Many of the biological tests, on the other hand, are fairly new to soil science, so the exact procedures to be followed and the meanings of the results are less universally agreed upon in the soils community.

Chemical Indicators	**Physical Indicators**	**Biological Indicators**
pH Organic matter Total carbon Total nitrogen Cation exchange capacity Major and minor nutrients Electrical conductivity Heavy metals and other plant toxins	Texture Bulk density Penetration resistance Aggregate stability Water holding capacity Infiltration rate Depth to hardpan Depth to watertable Porosity Erosive potential Aeration	Microbial biomass Earthworm populations Nematode populations Arthropod populations Mycorrihizal fungi Respiration rate Soil enzyme activities Pollutant detoxification Decomposition rate

Table 1. Commonly used indicators of soil health.

Table 1 shows some of the commonly used chemical, physical, and biological indicators of soil health. Not all of these indicators are tested for in all cases, while under some circumstances other indicators than those listed in the table may be tested (see also: *Land Quality Indicators: Monitoring and Evaluation*). This goes back to the idea, discussed earlier, that soil health does not mean the same thing in all circumstances. Exactly what constitutes a healthy soil depends on the local conditions under which the soil has formed, and on the use to which the soil is being put. Because of this, there is no single group of tests for soil health, and no single set of results from these tests that indicates a soil is healthy. When evaluating soil health, all the information gathered must be pooled, evaluated as a group, and conclusions reached on a case-by-case basis.

2. Organic Matter

Probably the single most important soil property relating to soil health is the organic matter content of the soil (SOM). This is because OM content has a profound influence on the chemical, physical, and biological properties of any given soil. Within normal natural ranges for mineral soils, increases in SOM usually have a positive influence on soil health while losses of SOM tend to have a negative impact.

Human management of the soil system has a significant impact on SOM. Intense mechanical cultivation of the soil leads to a significant loss of SOM for a number of reasons. Turning of the soil during plowing introduces oxygen, which stimulates microbial decomposition of SOM, and removes plant cover; this exposes the organic-rich top soil to erosion by wind or water.

Mechanical tillage chops organic residues into smaller pieces, making more surface area immediately available to decomposers, and also incorporates residues into the soil; this makes it easier for soil organisms to participate in the decomposition process of the residues. Manipulation of soil pH to near optimal levels for cropping purposes encourages SOM decomposition, as does drainage of soils that are too wet. Finally, removing large portions of crop residues, as straw for example, leaves fewer residues behind to replace SOM lost to natural decomposition processes. All these management activities improve crop yields over the short term but lead to significant losses of SOM over the long-term, putting sustainable crop production at jeopardy.

Improving SOM in agricultural fields has become a major focus of modern agricultural management because of the benefits mentioned above. These include: minimal or no-till techniques that reduce soil disturbance, maintenance of cover crops or residues on the surface, and avoidance of chopping and incorporation of such residues into the soil. Another significant management aspect is to leave as many crop residues as possible in the field, so that significant plant material remains available to be turned into SOM (see also: *Soil Engineering and Technology*) . Techniques such as these can improve SOM levels over systems that rely heavily on mechanical manipulation of the soil. Increased SOM leads to a number of improvements in soil physical, chemical, and biological properties, which in turn benefit agricultural yields and allow for sustainable cropping of the land.

2.1. Role of Organic Matter in Soil Physical Properties

The biggest influences of SOM on soil physical properties are related to aggregate formation and stability. In combination with the secretions of soil organisms, SOM decomposition produces mucus-like “glues” that help create and stabilize soil aggregates. In turn, these aggregates improve water infiltration by creating large pore spaces along the boundaries between the aggregates.

Large aggregates require more energy to erode than do smaller, individual mineral particles, and when a soil has large pores that increase infiltration less water runs off across the land surface. This combination of large aggregates and good infiltration makes a soil less erosion prone than similar soils with poor aggregation and infiltration (Figure 2).

Aggregates also improve water storage and aeration in the soil. Small pores within the aggregates are able to hold water through moderately dry periods. However, it is also important that soils contain adequate oxygen for respiratory processes. The large pores between aggregates allow for rapid drainage of water, followed by the movement of air into the large pores. Therefore, good aggregation is essential to achieve a balance between water content and air content in the soil.

Figure 2. Erosion from an unprotected field.
(Photo by Lynn Betts, USDA NRCS)

Resistance to root penetration generally decreases with increasing SOM content because roots are able to follow channels along aggregate boundaries. As the resistance to penetration is reduced, a soil also becomes easier to plow because it requires less energy to pull tillage implements through the soil. Therefore, the simple addition of organic materials to a soil can lead to a wide range of improved physical properties in that soil.

2.2. Role of Organic Matter in Soil Chemical Properties

Soil organic matter affects also chemical soil properties. Essential plant nutrients are released during the decay of SOM, including nitrogen, phosphorus, sulfur, potassium, calcium, magnesium, and others, meaning that SOM is a natural fertilizer. Some of these nutrients have other sources as well, for example calcium and magnesium released from mineral weathering, but SOM remains a major natural source of essential plant nutrients.

Increasing SOM complements the supply of nutrients from chemical fertilizers. The rate of SOM decomposition is controlled by factors that stimulate soil organisms, i.e. soil temperature and moisture content. This means that SOM usually decomposes slowly in spring, when soil temperature is fairly cool and soil microbes are not particularly active, but as the growing season progresses soil temperatures increase, soil microbiological activity increases and SOM decomposes more rapidly. As summer decomposition rates begin, chemical fertilizers are no longer needed in soils with high SOM. In other words, soils with adequate organic content do not need applications of chemical fertilizers at the same high rates as soils with lower organic contents. This means high levels of SOM can save on fertilizer costs and help avoid some of the environmental problems that can arise from high levels of fertilizer use.

Other important chemical properties affected by SOM are cation exchange capacity (CE) and buffering capacity. The humus in SOM has a CE of approximately 200-260 meq/100 g soil, which is high compared to clay. Therefore, increasing SOM levels increases overall soil CE, and increases the ability of a soil to store essential nutrients in cation form, such as NH_4^+, Ca^{+2}, Mg^{+2}, and K^+. High CE makes fertilization more efficient, as cation nutrients that are not immediately used by crops can be stored in the soil for future use.

Buffering capacity in soils is important because the pH of the soil, which is directly linked to base saturation, is important in determining nutrient availability. Fertilization often slightly acidifies the root zone, but a soil with a high buffering capacity resists such acidification. This means that soils with a high buffering capacity are more resistant to pH changes due to agricultural management, and are less likely to end up in an undesirable pH range.

2.3. Role of Organic Matter in Supporting the Soil Ecosystem

SOM has a profound effect on the numbers, kinds, and diversity of organisms in the soil because SOM is their basic energy source. Without sufficient SOM the soil food web is not well established and a healthy soil ecosystem does not develop. The presence of such an ecosystem is particularly important to farmers because it includes decomposers - organisms that break down dead organic materials. Without the actions of decomposers, essential plant nutrients would not be released from SOM, organic "glues" important in soil structure would not be formed, and many of the important chemical and physical benefits of SOM would not be realized (see also: *Soil Biology and Microbiology*).

The soil ecosystem and the role of the various organisms in it will later be discussed in greater detail, but for now it is important to note that adequate SOM is absolutely essential to establish a healthy soil ecosystem.

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http://www.sare.org/ (The USDA Sustainable Agriculture Research and Education website)

http://www.fao.org/agriculture/crops/en/ (FAO Plant Production and Protection homepage)

http://www.rodaleinstitute.org/ (Homepage of the Rodale Institute, which supports sustainable and organic farming)

http://www.soilandhealth.org/ (A free public library offering electronic versions of manuscripts on sustainable agriculture)

Biographical Sketch

Eric C. Brevik is an Associate Professor of Geology and Soils at Dickinson State University, North Dakota, USA. Dr. Brevik earned his BS and MA degrees in Geology from the University of North Dakota and his PhD in Soil Science at Iowa State University. He has taught courses in soil science and geology at Valdosta State University (Georgia, USA) and Dickinson State University since 2001. His research interests include carbon sequestration by soil, soil health and productivity, soils and society, and the integration of geological and soils information.

Dr. Brevik is active professionally, having published over 130 peer-reviewed articles, abstracts, and other publications. He is also working both in the United States and internationally in researching the historical and sociological aspects of soil science. He served as the vice chair and then the chair for the Soil Science Society of America's Council for the History, Philosophy, and Sociology of Soil Science from 2004-2006 and currently serves as the webmaster for the same group. As part of his chair duties, Dr. Brevik helped organize and chaired a session on Soils and Human Health at the 2006 Soil Science Society of America's meeting in Indianapolis, Indiana, USA. Dr. Brevik is also the current newsletter editor for the International Union of Soil Sciences Council for the History, Philosophy, and Sociology of Soil Science, and he helped organize and chaired a session on the History of Soil Science in Developing Countries at the 2006 World Congress of Soil Science in Philadelphia, Pennsylvania, USA.