NCF-Envirothon 2027 Maryland

Current Issues Part A Study Resources

Key Topic #1: Defining Soil Health

Learning Objectives

1. Define soil health in agricultural systems using key physical, chemical, and biological indicators.
2. Identify characteristics and management practices of healthy soils, including the seven attributes of soil health and strategies for reducing soil degradation and improving soil quality.
3. Evaluate soil health by identifying key indicators such as fertility, soil structure, depth, drainage and aeration, biological activity, absence of toxins, and resilience.
4. Explain how soil management practices affect soil health, including how tillage, organic matter, erosion, compaction, cover crops, crop rotations, and nutrient management can either improve or degrade soil quality.

Resource Title	Source	Page
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Healthy Soils Are: Well Structured	*Healthy Soils Are: Well Structured | USDA. (n.d.). Usda.Gov.*	7
Soil Health Key Points	*Soil Health Key Points | USDA. (n.d.). Usda.Gov.*	9
Healthy Soils, *Chapter 1*	*Magdoff, F., & Van Es, H. (2021). Building Soils For Better Crops Sustainable Soil Management, 4th edition (Chapter 1).*	10

UNIVERSITY OF MARYLAND EXTENSION | AgFS Agriculture & Food Systems

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Soil Health

By Sarah Hirsh, Ph.D.

What is soil health?

Soil health is "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" (Natural Resources Conservation Service, 2025). A healthy soil has characteristics that will help support healthy and productive plants. Soil health is a similar concept to soil quality, which has been defined as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran and Parkin, 1994). "Soil health" emphasizes that soil should be recognized as a living, breathing ecosystem, which is home to billions of organisms.

We can consider soil in terms of its physical, chemical, and biological components. Some of these characteristics are inherent to factors that we cannot control, while others can be influenced by management. Soil health focuses on those characteristics that we can influence through management. For example, in normal farming operations we do not change soil texture (the percent of sand, silt and clay), which affects how that soil functions. In comparison to a soil with a higher clay content, a sandier soil will have lower water-holding and nutrient-retention capacity. However, regardless of the texture of the soil, if we manage the soil with practices that increase organic matter, we will increase water-holding and nutrient-retention capacity. In other words, we can improve soil quality and soil health through management practices regardless of the inherent soil texture.

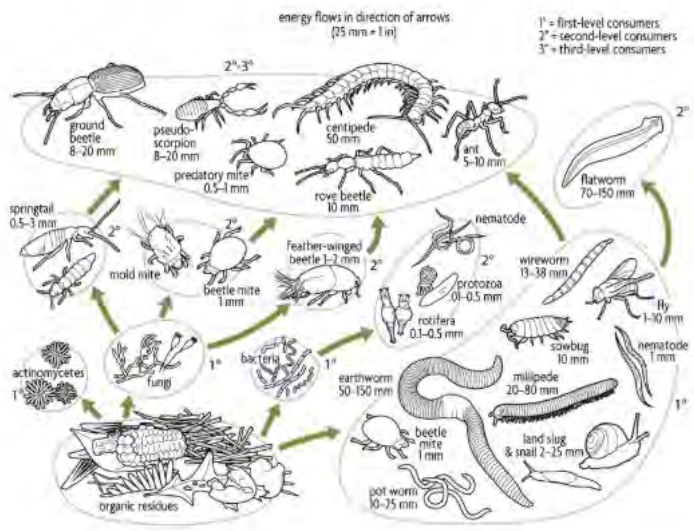

Figure 1. *The soil food web. Modified from D.L. Dindal (1972). Illustration by Vic Kulihin. (Magdoff and van Es, 2021)*

Economic benefits of maintaining and improving soil health

Improved soil health leads to better plant growth and quality, which can directly translate to increased yields and profits. Healthier soils are more resistant (can withstand) and resilient (can bounce back) to periods of environmental stress such as heavy rain, drought, or pest and disease outbreaks. Healthier soils tend to drain water better, allowing for increased field access during wet periods. Management that emphasizes soil health practices can lead to reduced input costs by decreasing losses and improving use efficiency of fertilizer, pesticide and herbicide, irrigation applications, and tillage passes (Moebius-Clune et al., 2016). Practices that support soil organisms typically will increase the sustainability and profitability of the farm.

Soil biology

Soil organisms coexist in an intricate food web fueled by organic residues and root exudates, and play a central role in soil health (Figure 1). One

teaspoon of agricultural soil typically contains 100 million to one billion bacteria, several meters of fungi, thousands of protozoa, and 10-20 nematodes (Fortuna, 2012). Soil organisms serve different roles and influence the physical and chemical components of soil.

Figure 2. Earthworm channeling through topsoil in no-till wheat field. Photo credit Sarah Hirsh.

Organisms such as predatory insects, predatory nematodes, and parasites can help regulate the soil ecosystem by keeping pest numbers in check (Hopwood at al., 2021).

Physical components influenced by organisms

Organisms such as earthworms, ants, termites, and plant roots can change the formation of soil or serve as soil engineers. They form channels through the soil that facilitate water and oxygen movement and dispersal (Figure 2). Most soil organisms and plant roots are aerobic and need oxygen. Plant roots, earthworms, and many other organisms release sticky exudates that improve soil aggregation. An aggregated topsoil will include both large pores for water infiltration/percolation and aeration and smaller pores that hold water.

Chemical components influenced by organisms

Organisms are responsible for nutrient cycling in the soil. Bacteria, fungi, and earthworms help decompose organic materials in the soil. Decomposing organisms can transform nutrients from organic to mineral forms, or elements from one form to another, such as nitrifying bacteria that transform ammonia to nitrite and nitrate in the nitrogen cycle. Nitrate is a mobile nutrient form readily accessible for plant uptake. Soil organic matter retains water and nutrients, which are then available for plant uptake. Dead organisms or root exudates also serve as a food source and energy for other organisms. A sufficient food supply of organic materials drives the soil food web and encourages all the other activities and services of organisms (Figure 1).

Symbiotic relationships that influence soil nutrients

Rhizobia bacteria and mycorrhizal fungi are two examples of soil organisms that have symbiotic relationships with plants. Rhizobia bacteria form nodules on legume plant roots (Figure 3). Those nodules serve as factories, in which rhizobia transform atmospheric nitrogen gas (N2), a form of nitrogen that cannot be taken up by plants, to ammonia nitrogen (NH3), the form of nitrogen readily used by plants. This process is called biological nitrogen fixation. In turn, the rhizobia bacteria receive food and energy from the plant (Flynn and Idowu, 2015).

Mycorrhizal fungi grow within plant roots. Their hyphae scavenge phosphorus, other nutrients, and water from the surrounding soil, which they provide to the plant. In turn, they receive energy in the form of sugars from the plant. The hyphae are 1/60 the diameter of the plant root and therefore have access to much smaller soil pores than the roots can access (Magdoff and van Es, 2021). Mycorrhizal-plant relationships form with most vascular plants, with exceptions including spinach, sugar beets, lupins, and brassicas.

Figure 3. *Soybean plant with root nodules housing rhizobia bacteria. Through the process of biological nitrogen fixation, rhizobia bacteria convert atmospheric nitrogen gas (N2) to plant-available ammonia nitrogen (NH3). Photos credit Ray Weil.*

Give it the Stake Test!

Does your soil have good structure? Give it the slake test! Ray Archuleta, an agronomist with the USDA Natural Resources Conservation Service with a passion for soil health, has done the test scores of times. Anyone can do it, he says, and he predicts it will open your eyes.

"What happens with poor soil structure is that the pores collapse in water and the soil breaks apart," Archuleta says. "Soil with good structure—the untilled soil—can still be intact for the most part even 24 hours later. The reason for the difference is soil structure. Biological cementing, the work of soil microbes, glues the aggregates of the untilled soils together."

In a similar test, an infiltration or rainfall simulation test, Archuleta puts the two soil samples in wire mesh inserted into empty jars, then simulates rainfall onto them.

"When you put a tilled soil and an un-tilled soil in yarn jars and simulate rainfall onto them, you quickly see the untilled soil allows the water to infiltrate the whole profile. On the other hand, water stays on top of the tilled soil much longer," Archuleta says.

Continued on back

unlock the SECRETS IN THE SOIL

"SOFT AND CRUMBLY." "LIKE COTTAGE CHEESE." "LIKE A SPONGE." "LOOSE AND FULL OF HOLES."

Those and other common descriptions of what healthy soil looks and feels like refer to good soil structure.

Soil structure, the arrangement of the solid parts of the soil and the pore space between them, is critical to how the soil functions. When the solid parts—sand, silt and clay particles—cling together as coarse, granular aggregates, the soil has a good balance of solid parts and pore space.

Highly aggregated soils—those granular, durable, distinct aggregates in the topsoil that leave large pore spaces between them—are soils with good tilth and good structure.

Well-structured soils have both macropores (large soil pores generally greater than 0.08 mm in diameter) and micropores (small soil pores with diameters less than 0.08 mm that are usually found within structural aggregates).

An interconnected network of pores associated with loosely packed, crumbly, highly aggregated soils allows rapid infiltration and easy movement of both water and air through the soil and provides habitat for soil organisms.

Chemical and physical factors play a prominent role in small aggregate formation in clay soils, while biological processes drive development of large aggregates and macropores. Earthworms, for instance, produce both new aggregates and pores. Their binding agents are responsible for the formation of water-stable, macro-aggregates, and their burrowing creates continuous pores linking surface to subsurface soil layers. As they feed, earthworms also speed plant residue decomposition, nutrient cycling, and redistribution of nutrients in the soil profile.

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HEALTHY SOILS ARE: *well-structured.*

Soil organic matter also helps develop stable soil aggregates. Soil microorganisms that are fed with organic matter secrete a gooey protein called glomalin, an effective short-term cementing agent for large aggregates. Organic glues are produced by fungi and bacteria as they decompose plant residues. Water-resistant substances produced by microorganisms, roots, and other organic matter, provide long-term aggregate stability from a few months to a few years.

TILAGE DESTROYS STRUCTURE

Management practices that reduce soil cover, disrupt continuous pore space, compact soil, or reduce soil organic matter, negatively impact soil structure. Since tillage negatively affects all of these properties, it's high on the list of practices damaging to healthy soils.

When tillage loosens the soil, it leaves soil particles exposed to the forces of wind and water. Transported by wind and water, detached soil particles settle into pores, causing surface sealing, compaction and reduced infiltration. When this happens less water is available to plants and runoff and erosion increases.

By contrast, soils that are not tilled and are covered with diverse, high residue crops throughout the year have better soil structure, are highly aggregated, with high levels of organic matter and microorganism activity, high water holding capacity, high infiltration rates, and little compaction.

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"I think these tests are powerful visual tools to help explain and help people remember how soils function" Archuleta continues. "I used to think if I tilled the soil—fluffed it up—it would allow more water in. But that's just not true. Tilling soil closes pore space and keeps rainfall from infiltrating. You've got to have pore space in your soil from top to bottom."

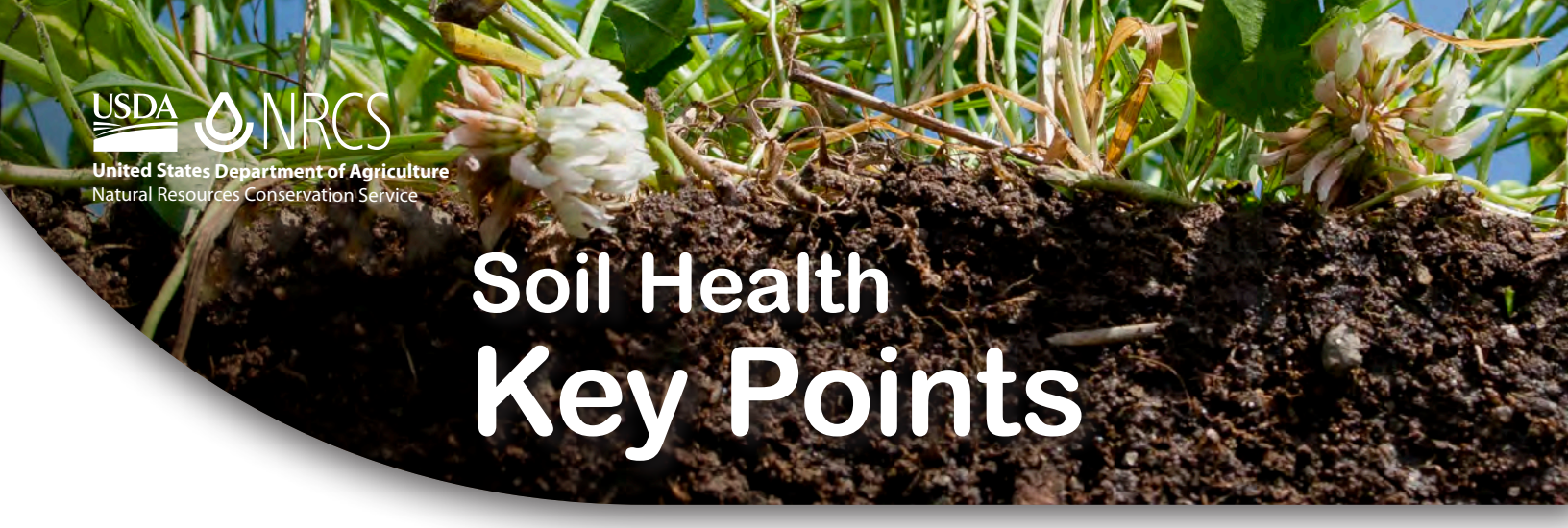
"The tests tell me in our watersheds we have an infiltration problem, not a runoff problem," he concludes. "What I mean is, if we focus on building healthy soils that result in more infiltration, we'll do what we need to do to eliminate much of the runoff."

How to do the Slake Test

The slake test compares two chunks of topsoil in water to see how well and how long they will hold together. Here are the steps:

1. Collect a chunk of topsoil—a size that would fit in your hand—from an area where you don't till, like a fencerow, or a field you've no-tilled or had in grass for many years.
2. Get a second spade-full or chunk of soil from a field you've tilled consistently. It should be the same soil type as the first sample.
3. Find two glass jars, yarn jars or some kind of clear glass jars large enough to hold the chunks of soil.
4. Put together some type of wire mesh that you can hook at the top of each jar that will allow the soil to be submerged in the water, yet be held within the top half of the jar.
5. Insert the wire meshes into each jar.
6. Fill the jars with water.
7. At the same time, submerge the tilled sample in one jar, and the untilled sample in the other.
8. Watch to see which soil holds together and which one falls apart. The soil with poor structure is the one that will begin to fall apart.

If you want to see "Ray the Soil Guy" demonstrate the test or the infiltration test, checkout our online resources.



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Soil Health
Key Points

unlock the SECRETS IN THE SOIL

What's critical about soil health now?

1. World population is projected to increase from 7 billion in 2013 to more than 9 billion in 2050. To sustain this level of growth, food production will need to rise by 70 percent.
2. Between 1982–2007, 14 million acres of prime farmland in the U.S. were lost to development.
3. Improving soil health is key to long-term, sustainable agricultural production.

Soil health matters because:

1. Healthy soils are high-performing, productive soils.
2. Healthy soils reduce production costs—and improve profits.
3. Healthy soils protect natural resources on **and** off the farm.
4. Franklin Roosevelt's statement, "The nation that destroys its soil destroys itself," is as true today as it was 75 years ago.
5. Healthy soils can reduce nutrient loading and sediment runoff, increase efficiencies, and sustain wildlife habitat.

What are the benefits of healthy soil?

1. Healthy soil holds more water (by binding it to organic matter), and loses less water to runoff and evaporation.
2. Organic matter builds as tillage declines and plants and residue cover the soil. Organic matter holds 18-20 times its weight in water and recycles nutrients for plants to use.
3. One percent of organic matter in the top six inches of soil would hold approximately 27,000 gallons of water per acre!
4. Most farmers can increase their soil organic matter in **three to 10 years** if they are motivated about adopting conservation practices to achieve this goal.

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Chapter 1

HEALTHY SOILS

All over the country [some soils are] worn out, depleted, exhausted, almost dead. But here is comfort: These soils possess possibilities and may be restored to high productive power, provided you do a few simple things.

—C.W. BURKETT, 1907

It should come as no surprise that many cultures have considered soil central to their lives. After all, people were aware that the food they ate grew from the soil. Our ancestors who first practiced agriculture must have been amazed to see life reborn each year when seeds placed in the ground germinated and then grew to maturity. In the Hebrew Bible, the name given to the first man, Adam, is the masculine version of the word "earth" or "soil" (*adama*). The name for the first woman, Eve (or Hava in Hebrew), comes from the word for "living." Soil and human life were considered to be intertwined. A particular reverence for the soil has been an important part of the cultures of many civilizations, including Native American tribes. In reality, soil *is* the basis of all terrestrial life. We humans are derived from soil. Aside from when we eat fish and other aquatic organisms, we obtain the essential elements in our bodies, such as the calcium and phosphorus in our bones and teeth, the nitrogen in our proteins, the iron in our red blood cells, and so on, all by directly or indirectly consuming plants that took these from the soil.

Although we focus on the critical role soils play in growing crops, it's important to keep in mind that soils also provide other important services. Soils govern whether rainfall runs off the field or enters the ground and eventually helps recharge underground aquifers. When a soil is stripped of vegetation and starts to degrade, excessive runoff and flooding are more common. Soils also absorb, release and transform many different chemical compounds. For example, they help to purify wastes flowing from the septic system drain fields in your backyard. Soils also provide habitats for a diverse group of organisms, many of which are very important, such as those bacteria that produce antibiotics and fungi that help plants obtain nutrients and water and improve soil structure. Soil organic matter stores a huge amount of atmospheric carbon. Carbon, in the form of carbon dioxide, is a greenhouse gas associated

Photo by Dan Anderson

with global warming. So, by increasing soil organic matter, more carbon can be stored in soils, reducing the potential for climate change. We also use soils as a foundation for roads, industry and our communities.

HOW IS SOIL MADE?

Before we consider what makes a soil rich or poor, we should learn how it comes into existence. Soil consists of four parts: solid mineral particles, water, air and organic matter. The particles are generally of sand, silt and clay size (and sometimes also larger fragments) and were derived from weathering of rocks or deposition of sediments. They mainly consist of silicon, oxygen, aluminum, potassium, calcium, magnesium, phosphorus, potassium and other minor chemical elements. But these elements are generally locked up in the crystalline particles and are not directly available to plants. However, unlike solid rock, soil particles have pore spaces in between them that allow them to hold water through *capillary action*: the soil can act like a sponge. This is an important process because it allows the soil water, with the help of carbon dioxide in the air, to very slowly dissolve the mineral particles and release nutrients—we call this *chemical weathering*. The soil water and dissolved nutrients, together referred to as the *soil solution*, are now available for plants. The air in the soil, which is in contact with the air above ground, provides roots with oxygen and helps remove excess carbon dioxide from respiring root cells.

What role do plants and soil organisms play? They facilitate the cycling of organic matter and of the nutrients, which allows soil to continue supporting life. Plants' leaves capture solar energy and atmospheric carbon from carbon dioxide (CO_2) through photosynthesis. The plant uses this carbon to build the sugars, starches and all the other organic chemicals it needs to live and reproduce. At the same time, plant roots absorb both soil water and the dissolved nutrients (nitrogen is added to soils or directly to plants through associated biological processes). Now, the mineral nutrients that were derived from the soil are stored in the plant biomass *in organic form* in combination with the carbon from the atmosphere. The seeds tend to be especially high in nutrients, but the stems and leaves also contain important elements. Eventually plants die and their leaves and stems return to the soil surface. Sometimes plants don't return directly to the soil surface, but rather are eaten by animals. These animals extract nutrients and energy for themselves and then defecate what remains. Soil organisms help to incorporate both manure and plant residues into the soil, while the roots that die, of course, are already in the soil. This dead plant material and manure become a feast for a wide variety of organisms—beetles, spiders, worms, fungi, bacteria, etc.—that in turn benefit from the energy and nutrients the plants had previously stored in their biomass. At the same time, the decomposition of organic material makes nutrients available again to plants, now completing the cycle.

But is it a perfect cycle? Not quite, because it has not evolved to function under intensive agricultural production. The chemical weathering process that adds new nutrients into the cycle continues at a very slow pace. On the other end of the cycle the soil captures some of the organic matter and puts it "in storage." This happens because soil mineral particles, especially clays, form bonds with the organic molecules and thereby protect them from further decomposition by soil organisms. In addition, organic matter particles inside soil aggregates are protected from decomposition. Over a long time, the soil builds up a considerable reservoir of nutrients from slowly decomposing minerals and carbon, and of energy from plant residue in the form of organic matter—similar to putting a small amount of money into a retirement account each month. This organic matter storage system is especially impressive with prairie and steppe soils in temperate regions (places like the central United States, Argentina and Ukraine) because natural

grasslands have deep roots and high organic matter turnover (Figure 1.1).

In a natural system this process is quite efficient and has little nutrient leakage. It maximizes the use of mineral nutrients and solar energy until the soil has reached its maximum capacity to store organic matter (more about this in Chapter 3). But when lands were first developed for agriculture, plowing was used to suppress weeds and to prepare the soil for planting grain crops. Plowing was also beneficial because it accelerated organic matter decomposition and released more nutrients than unplowed land. This was a major rift in organic matter cycling, because it caused more organic matter to be lost each year than was returned to the soil. In addition, a related rift occurred in nutrient cycling as some of the nutrients were harvested as part of the crop, removed from the fields and never returned. Other nutrients were washed out of the soil. Over time, the organic matter bank account that had slowly built up under natural vegetation was being drawn down.

However, until organic matter became seriously depleted, its increased decomposition through tillage helped to supply crops with released nutrients and these rifts did not cause widespread concern. On sloping lands these losses went much faster because the organic matter near the surface also eroded away after the soil was exposed to rain and wind. Only in the past century did we find effective ways to replenish the lost nutrients by applying fertilizers that are derived from geologic deposits or the Haber-Bosch process for producing nitrogen fertilizers. But the need to replace the organic matter (carbon) was mostly ignored until recently.

The organic matter in the soil is more complex and plays many important roles in soils that we will discuss in Chapter 2. Not only does it store and supply nutrients and energy for organisms, it also helps form aggregates when mineral and organic particles clump together. When it is made up of large amounts of different-sized aggregates, the soil contains more spaces for storing water and allowing gas exchange, as oxygen enters for use by plant roots and by soil organisms and the carbon dioxide produced by organisms leaves the soil. So in summary, the mineral particles and pore spaces form the basic structure of the soil, but the organic matter is mostly what makes it *fertile*.

Figure 1.1. Soils build a storage reservoir of carbon and nutrients in organic matter, and can also hold water and air. The organic matter builds up from decayed plant material and accumulates mostly in the dark root zone under the surface. Photo by USDA-NRCS.

WHAT KIND OF SOIL DO YOU WANT?

Farmers sometimes use the term *soil health* to describe the condition of the soil. Scientists usually use the term *soil quality*, but both refer to the same idea: how well the soil is functioning for whatever use is being considered. The concept of *soil health* focuses on the human factor—the *anthropogenic* influence—that is increasingly significant due to many years of intensive management. This is different from the inherent

differences in soils that are the result of the natural factors that formed the soil, such as the parent material, climate, etc. Thereby, an analogy with humans is apt: We may have some natural differences from our genetic backgrounds (taller or shorter, fairer or darker, etc.), but our health still strongly affects the way we can function and is greatly influenced by how we treat our bodies.

In agriculture, soil health becomes a question of how good the soil is at supporting the growth of high-yielding, high-quality and healthy crops. Given this, how then would you know a high-quality soil from a lower-quality soil? Most farmers and gardeners would say they know one when they see one. Farmers can certainly tell you which of the soils on their farms are of low, medium or high quality, and oftentimes they refer to how dark and crumbly it is. They know high-quality soil because it generates higher yields with less effort. Less rainwater runs off and fewer signs of erosion are seen on the better-quality soils. Less power is needed to operate machinery on a healthy soil than on poor, compacted soils. But there are other characteristics that we'd like a soil to have. These can be condensed into seven desirable attributes of healthy soils:

1. **Fertility**. A soil should have a sufficient supply of nutrients throughout the growing season.
2. **Structure**. We want a soil with good tilth so that plant roots can fully develop with the least amount of effort. A soil with good tilth is more spongy and less compact than one with poor tilth. A soil that has a favorable and stable soil structure also promotes rainfall infiltration and water storage for plants to use later.
3. **Depth**. For good root growth and drainage, we want a soil with sufficient depth before a compact soil layer or bedrock is reached.
4. **Drainage and aeration**. We want a soil to be well drained so that it dries enough in the spring and during the following rains to permit timely field operations. Also, it's essential that oxygen is able to enter the root zone and just as important that carbon dioxide leaves it (it also enriches the air near the leaves as it diffuses out of the soil, allowing plants to have higher rates of photosynthesis). Keep in mind that these general characteristics do not necessarily hold for all crops. For example, flooded soils are desirable for cranberry and paddy rice production.
5. **Minimal pests**. A soil should have low populations of plant disease and parasitic organisms. Certainly, there should also be low weed pressure, especially of aggressive and hard-to-control weeds. Most soil organisms are beneficial, and we certainly want high amounts of organisms that help plant growth, such

THINK LIKE A ROOT!

If you were a root, what would you like from an ideal soil? Surely you'd want the soil to provide adequate nutrients and to be porous with good tilth, so that you could easily grow and explore the soil and so that the soil could store large quantities of water for you to use when needed. But you'd also like a very biologically active soil, with many beneficial organisms nearby to provide you with nutrients and growth-promoting chemicals, as well as to keep potential disease organism populations as low as possible. You would not want the soil to have any chemicals, such as soluble aluminum or heavy metals, that might harm you; therefore, you'd like the pH to be in a proper range for you to grow, and you wouldn't want to be in a soil that somehow became contaminated with toxic chemicals. You would also not want any subsurface layers that would restrict your growth deep into the soil.

as earthworms and many bacteria and fungi.

6. **Free of toxins**. We want a soil that is free of chemicals that might harm the plant. These can occur naturally, such as soluble aluminum in very acid soils or excess salts and sodium in arid soils. Potentially harmful chemicals also are introduced by human activity, such as fuel oil spills or when sewage sludge with high concentrations of toxic elements is applied.
7. **Resilience**. Finally, a high-quality soil should resist being degraded. It should also be resilient, recovering quickly after unfavorable changes like compaction.

THE NATURE AND NURTURE OF SOILS

Some soils are exceptionally good for growing crops and others are inherently unsuitable, but most are in between. Many soils also have limitations, such as low organic matter content, texture extremes (coarse sand or heavy clay), poor drainage or layers that restrict root growth. Midwestern loess-derived prairie soils are naturally blessed with a combination of a silt loam texture and high organic matter content. By every standard for assessing soil health, these soils, in their virgin state, would rate very high. But even many of these prairie soils required drainage in order for them to be highly productive.

The way we care for, or *nurture*, a soil modifies its inherent nature. A good soil can be abused through years of poor management and can turn into one with poor health, although it generally takes a lot of mistreat ment to reach that point. On the other hand, an innately challenging soil may be very "unforgiving" of poor management and quickly become even worse. For example, a heavy clay loam soil can be easily compacted and turned into a dense mass. Naturally good and poor soils will probably never reach parity through good farming practices because some limitations simply cannot be completely overcome, but both can be productive if they are managed well.

HOW DO SOILS BECOME DEGRADED?

Although we want to emphasize healthy, high-quality soils because of their ability to produce high yields of crops, it is also crucial to recognize that many soils in the United States and around the world have become degraded: they have become "worn out." Degradation most commonly begins with tillage—plowing and harrowing the soil—causing soil aggregates to break apart, which then causes more rapid loss of soil organic matter as organisms have greater access to residues. This accelerates erosion, because soils with lower organic matter content and less aggregation are more prone to accelerated erosion. And erosion, which takes away topsoil enriched with organic matter, initiates a downward spiral resulting in poor crop production. Soils become compact, making it hard for water to infiltrate and for roots to develop properly. Erosion continues and nutrients decline to levels too low for good crop growth. The development of saline (too salty) soils under irrigation in arid regions is another cause of reduced soil health. (Salts added in the irrigation water need to be leached beneath the root zone to avoid the problem.)

Soil degradation caused significant harm to many early civilizations, including the drastic loss of productivity resulting from soil erosion in many locations in the Middle East (such as present day Israel, Jordan, Iraq and Lebanon) and southern Europe. This led either to colonial ventures to help feed the citizenry—like the Romans invading the Egyptian breadbasket—or to the decline of the civilization. The only exceptions were the convergence zones in the landscapes, valleys and deltas where the nutrients and sediments flow together and fertility can be maintained for many centuries (more about this in Chapter 7).

Tropical rainforest conditions (high temperature and rainfall, with most of the organic matter near the soil surface) may lead to significant soil degradation within two or three years of conversion to cropland. This is the reason the "slash and burn" system, with

Figure 1.2. Agricultural soil (left) and natural soil (grassland; right) from adjacent sites in the U.S. Great Plains. Agricultural soil has lower soil organic matter and higher density. Photos by Kirsten Kurtz.

people moving to a new patch of forest every few years, developed in the tropics. After farmers depleted the soils (the readily decomposed organic matter) in a field, they would cut down and burn the trees in the new patch, allowing the forest and soil to regenerate in previously cropped areas.

The westward push of U.S. agriculture was stimulated by rapid soil degradation in the East, originally a zone of temperate forest. Under the environmental conditions of the Great Plains (moderate rainfall and temperature, with organic matter distributed deeper in the soil), it took many decades for the effects of soil degradation to become evident (Figure 1.2).

The extent of deteriorating soil on a worldwide basis is staggering: Soil degradation has progressed so far as to decrease yields on about 20% of all the world's cropland and on 19–27% of the grasslands and rangelands. The majority of agricultural soils are in only fair, poor or very poor condition. Erosion remains a major global problem, robbing people of food and each year continuing to reduce the productivity of the land. Each year some 30–40 billion tons of topsoil are eroded from the croplands of the world.

HOW DO YOU BUILD A HEALTHY, HIGH-QUALITY SOIL?

Some characteristics of healthy soils are relatively easy to achieve. For example, an application of ground limestone will make a soil less acid and will increase the availability of many nutrients to plants. But what if the soil is only a few inches deep? In that case, there is little that can be done within economic reason, except on a very small, garden-size plot. If the soil is poorly drained because of a restricting subsoil layer of clay, tile drainage can be installed, but at a significant cost economically and environmentally.

We use the term *building soils* to emphasize that the nurturing process of converting a degraded or low-quality soil into a truly high-quality one requires understanding, thought and significant actions. It is a process that mirrors the building of soil through natural processes where plants and organic matter are key elements. This is also true for maintaining or

> ... 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.
>
> —PLATO, 4TH CENTURY B.C.

EVALUATING YOUR SOILS

Score cards and laboratory tests have been developed to help farmers assess their soils, using scales to rate the health of soils. In the field, you can evaluate the presence of earthworms, severity of erosion, ease of tillage, soil structure and color, extent of compaction, water infiltration rate and drainage status. Doing some digging can be especially enlightening! Then you rate crops growing on the soils by such characteristics as their general appearance, growth rates, root health, degree of resistance to drought and yield. It's a good idea for all farmers to fill out such a scorecard for every major field or soil type on your farm every few years, or, alternatively, to send in soil to a lab that offers soil health analyses. But even without doing that, you probably already know what a really high-quality and healthy soil—one that would consistently produce good yields of high-quality crops with minimal negative environmental impact—would be like. You can read more on evaluating soil health in Chapter 23.

improving already healthy soils. Soil organic matter has a positive influence on almost all of the characteristics we've just discussed. As we will see in chapters 2 and 8, soil organic matter is even critical for managing pests. Appropriate organic matter management is, therefore, the foundation for high-quality soil and for a more sustainable and thriving agriculture. It is for this reason that so much space is devoted to organic matter in this book. However, we cannot forget other critical aspects of management, such as trying to lessen soil compaction and good nutrient management.

Although the details of how best to create high-quality soils differ from farm to farm and even field to field, the general approaches are the same. For example:

- **Minimize tillage** and other soil disturbances to maintain soil structure and decrease losses of native soil organic matter.
- **Implement a number of practices** that add diverse sources of organic materials to the soil.
- **Maximize live roots** in the soil and use **rotations and cover crops** that include a diverse mix of crops with different types of root systems.
- **Provide plenty of soil cover** through cover crops and/or surface residue even when economic crops aren't present in order to protect the soil from raindrops and temperature extremes.
- Whenever traveling on the soil with field equipment, use practices that help **develop and maintain good soil structure**.
- Manage **soil fertility** status to maintain optimal pH levels for your crops and a sufficient supply of nutrients for plants without contributing to water pollution.
- In arid regions, reduce the amount of **sodium or salt** in the soil.

There are also large-scale considerations related to the structure of agriculture and associated nutrient and carbon flows that tie into this. Later in the book we will return to these and other practices for developing and maintaining healthy soils.

SOIL HEALTH, PLANT HEALTH AND HUMAN HEALTH

Of the literally tens of thousands of species of soil organism, relatively few cause plant diseases. And the same is true for human diseases, with examples such as tetanus (a toxin produced by a bacterium), hookworm (a nematode), and ringworm (a fungus). But the physical condition of soil can also affect human health. For example, people in the path of dust storms, which pick up fine particles from bare soils, may have significant

respiratory problems and damaged lung tissue. In general, soils with a high degree of biological diversity, good soil structure and continual cover with living plants will be healthier for people as well as the plants growing in them. In fact, frequent contact with soil and farm animals early in life results in fewer allergies and stimulates the immune system, helping it to better respond to infections as one grows older.

We discuss soil degradation in this chapter because protecting soil's productivity and limiting environmental impacts are important objectives in and of themselves. However, there are ongoing debates around the world about whether improved soil health also translates into better-quality food and human health outcomes. Soils are the primary source of minerals for humans and animals, but can soil degradation eventually lead to nutrition and health problems? Also, is organically produced food healthier than conventional foods?

To answer these questions we need to understand the two main components of the food chain: how soil health affects plant health and how plant health subsequently affects human health. Together, this is the soil-plant-human health connection. For our discussion we'll ignore the impacts of intermediate steps of food processing, diets and food sourcing, although these can also have significant impacts.

Soils provide plants with nutrients and water, but this doesn't always happen in an optimal way. Healthy plants require *essential* nutrients like nitrogen, phosphorus, potassium and other major and minor elements discussed in Chapter 18. Other elements are not essential but are considered *beneficial* because they have a positive effect on plant growth or help the uptake of other elements. These are typically taken up by plants in trace amounts. A third category is *toxic* elements that are detrimental to plants at certain concentrations. Sometimes, elements are essential or beneficial at low concentrations and may become toxic at high concentrations, like copper and iron.

Nutrient Deficiencies

When crops are grown over many years, nutrients in soil are steadily absorbed by plants. In natural ecosystems the nutrients in plant material are mostly cycled back to the soil, but agricultural systems generally remove many of these nutrients from the farm when the harvested crops are sold, with variable amounts of nutrients remaining on the farm in residues, depending on the crop. (We discuss cycles and flows in Chapter 7). With the use of synthetic fertilizers some nutrients, notably nitrogen, phosphorus, potassium and calcium, are being replenished, but the minerals needed in small or trace amounts generally don't get replaced. This is especially the case in developing countries where farmers often don't analyze their soils and they apply standard fertilizer blends. Sometimes this is aggravated by compaction problems, when the minerals may be present in deeper soil layers but are not root accessible. In some cases soils are naturally deficient in essential elements that may affect plants, animals or humans. For example, selenium is naturally low in the northeastern and northwestern United States. It does not affect plants much but can cause problems with animals and humans.

Toxicities

Many elements in soil can become toxic to plants, animals or humans. The most egregious cases tend to be associated with some type of pollution from human activities. For example, heavy metals may have accumulated from atmospheric deposition of industrial smokestack emissions or from acid deposition from coal-fired power plants. In other cases agricultural activities themselves cause problems, like the long-term use of fertilizers containing high levels of cadmium. An unusual case involved the introduction of tube wells in Bangladesh to irrigate rice. The groundwater source contains naturally high levels of arsenic, which accumulates in the rice grains, causing serious health concerns with local populations. (A common

occurrence in regions of grain crop production is the over application of nitrogen fertilizer, which can lead to high concentrations of nitrate in drinking water, which adversely affects the health of rural residents. Although this problem is not a result of direct consumption of plants, it is directly related to how we grow crops.)

Another issue is that crops growing on soils low in biodiversity, in which plant disease organisms flourish, are generally treated with pesticides (fungicides, insecticides, nematicides). These chemicals, as well as herbicides, may find their way into the foods we eat, sometimes into the groundwater we drink. There has been a link established between a number of pesticides in the environment and human diseases.

Human Health Effects

It is difficult to scientifically prove effects of soil health on human health, in part due to the complexity of diets and ethical considerations around clinical trials involving humans. The most significant effect of soil degradation relates to the reduced ability to produce sufficient nutritious foodstuffs to meet peoples' basic caloric and protein needs. Especially in isolated rural areas in developing countries people depend on crops and animals raised on their own farms with little opportunity to buy additional food. Degraded soils and weather extremes can cause crop losses and significantly impact the food supply, with especially high concerns for the long-term impacts to children.

A secondary problem associated with soil degradation is deficiencies of essential minerals, especially in soils that are naturally of low fertility. Again, this may be a problem in regions with mineral mining and heavy dependence on local grain-dominated diets. In developed societies nutritional deficiencies are rare because people obtain food from diverse sources. For example, regional soil selenium deficiency does not impact people when they also eat nuts from other regions. (In developed societies, the concern is increasingly about unhealthy diet choices and the affordability of healthy food.)

Humans also benefit from organic plant compounds that may be indirectly linked to soil health, like the protein content in grains (related to nitrogen in soil), or so-called *secondary metabolites* that have beneficial health effects, like antioxidant activity (for example, phenolics and anthocyanins). A question is whether we can link the benefits of better soil management to actual higher human health outcomes. For example, organic management requires certain practices that enhance soil health because it involves integrated nutrient and organic matter management through better use of rotations and organic amendments. But will it also improve food quality and human health? Many people choose organic foods due to concerns about pesticides (which is a real potential health issue that we should be aware of) or because they believe it tastes better. Or they feel strongly about supporting farmer livelihoods and reducing environmental impacts. There is no evidence that nutrients from organic sources affect human health differently than those from synthetic or processed sources, because either way plants take up the nutrients almost exclusively as inorganic forms. Some studies have shown that organically produced food can positively impact some indicators such as increased levels of antioxidants. But due to many other confounding factors (people who eat organic food typically have better diets, healthier lifestyles, and are wealthier), no study has been able to definitively correlate those with positive human health outcomes.

A LARGER VIEW

In this book we discuss the ecological management of soils. And although the same basic principles discussed here apply to all soils around the world, the problems may differ in specifics and intensity, and different mixes of solutions may be needed on any particular farm or in any ecological zone. It is estimated that close to half the people in the world are deficient in nutrients and

vitamins and that half the premature deaths that occur globally are associated with malnutrition. Part of the problem is the low amount of nutrient-rich foods such as vegetables and fruits in diets. When grains form too large a part of the diet, even if people obtain sufficient calories and some protein, the lack of other nutrients results in health problems. Although iron, selenium, cobalt and iodine deficiencies in humans are rare in the United States, they may occur in developing countries whose soils are depleted and nutrient poor. It frequently is an easier and healthier solution to get these nutrients into peoples' diets by increasing plant content by adding these essential elements to the soil (or through irrigation water for iodine) rather than to try to provide everyone with supplements. Enhancing soil health—in all its aspects, not just nutrient levels—is probably one of the most essential strategies for providing nutritious food to all the people in the world and ending the scourge of hunger and malnutrition.

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