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Exploring the Physical, Chemical and Biological Components of Soil: Improving Soil Health for Better Productive Capacity

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Exploring the Physical, Chemical and Biological Components of Soil: Improving Soil Health for Better Productive Capacity

Abstract

"Soil health" is a term that is used to describe soil quality. The U.S. Department of Agriculture's Natural Resources Conservation Service has defined soil health as "The continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans (NRCS 2018)." For a farmer, soil health is the productive capacity of the soil, or the capacity of the soil to produce a crop or pasture. Healthy soils produce more and with better quality.

Soil health is critical for water and nutrient cycling. Soil captures rainwater and stores it for use by plants. Soil health is important to improve both the amount of water and nutrients that a soil can hold, and the availability of water and nutrients for plants. The storage of water and nutrients and subsequent transfer to plants are critical determinants of the productive capacity of the soil, and the soil health.

Here, we explore the fundamental components of soil, and how each component contributes to soil health and soil productive capacity.

Keywords

Soil health, tillage, cover crops

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Cover Page Footnote

We gratefully acknowledge the cooperation of the participating farmers in providing us access to their land.

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Exploring the Physical, Chemical and Biological Components of Soil: Improving Soil Health for Better Productive Capacity

G.F. Sassenrath, K. Davis, A. Sassenrath-Cole, and N. Riding

Summary

Soil health depends on the physical, chemical, and biological composition of the soil. Improving the soil health can improve the productive capacity of the soil, producing more crops and of higher quality. Soil health is affected by management practices, including tillage, crop rotations, and cover crops.

Introduction

"Soil health" is a term that is used to describe soil quality. The U.S. Department of Agriculture's Natural Resources Conservation Service has defined soil health as, "The continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans (NRCS 2018)." For a farmer, soil health is the productive capacity of the soil, or the capacity of the soil to produce a crop or pasture. Healthy soils produce more and with better quality.

Soil health is critical for water and nutrient cycling. Soil captures rainwater and stores it for use by plants. Soil health is important to improve both the amount of water and nutrients that a soil can hold, and the availability of water and nutrients for plants. The storage of water and nutrients and subsequent transfer to plants are critical determinants of the productive capacity of the soil, and the soil health.

Here, we explore the fundamental components of soil, and how each component contributes to soil health and soil productive capacity.

Soil Physical Components

Soil has physical, chemical, and biological components. The physical components of soil are well-studied and comprise the rocks and minerals that have been broken up over time into very small particles of sand, silt, and clay. These compounds are regularly measured to classify the texture of the soil. Sand is the coarsest material (50 µm (microns) – 2 mm) and can be easily seen or felt in a soil sample as rough particles. Silt particles are smaller than sand (2 – 50 µm; Figure 1), while clay particles are very small (less than 2 µm) The relative proportions of sand, silt, and clay determine the soil textural classification, visualized on the US Soil Texture Triangle (Figure 2). The textural composition of soil is determined by the soil formation processes that are regulated by time, topography, climate, living organisms, and the parent material, for example the underlying rock. In southeast Kansas, limestone is a common parent material. Some soils are developed from erosion. Wind and water can carry soil and deposit it in new areas, creating loess (wind-blown) or alluvial (water-borne) soils. A silt loam soil has 20 to 50% sand, 75 to 90% silt, and 0 to 30% clay. In contrast, a silty clay loam has 0 to 20% sand, 60 to 70% silt, and 25 to 40% clay.

The US Soil Texture Triangle classifies soils by composition (Figure 2). Claypan soils, common to southeast Kansas, were formed by the downward movement of small clay particles in the soil profile, and accumulation of the clay particles into a clay layer. This clay layer restricts the movement of water within the soil profile as the clay particles tightly bind water. The clay layer can also restrict root growth because of its high bulk density. Bulk density is a measure of the soil structure and the weight of the soil within a given volume. A friable soil has lower bulk density, better soil structure, and allows easier seedling germination than a compacted soil with high bulk density.

Soil was sampled from several locations and at increasing depths in the soil profile in crop production fields in southeast Kansas and analyzed for soil texture. In a typical field in southeast Kansas the soil changes from silt loam on the surface to silty clay loam and silty clay with increasing depth in the soil profile (Figure 2A). After about 12 inches in the soil profile, the soil texture is clay.

One serious result of tillage is the loss of topsoil (Figure 2B). As the productive silt loam topsoil is eroded away, the unproductive clay layer is exposed, as measured by the clay soil at 3 inches at some locations in Field 2. This loss of topsoil and increase in clay content reduces the productive capacity of the soil. The change in soil texture also alters the electrical resistivity (Mathis et al., 2018), as clay has higher electrical conductivity (and hence lower electrical resistivity) than sand or silt. The change in electrical resistivity of soil with texture is being used to map the clay layer and understand mechanisms of erosion in clay soils.

Management practices, including tillage, crop rotations, and cover crops alter the structure of the soil (Figure 3). Historically, we thought tillage was required to provide good soil structure for crop production by breaking up soil compaction. More recent research has shown that while tillage initially breaks up the soil structure and reduces compaction, tillage is not good for soil structure in the long term as tillage actually increases the compaction of the soil (NRCS, 2018). Soils managed with reduced or no tillage have better soil structure, improving seedling establishment and plant growth. Reducing soil tillage also improves the biological components of the soil by maintaining roots and microbial networks which in turn improve the overall soil health. A good physical composition is the first ingredient of a healthy soil but changing the soil physical composition is very difficult. Soil structure can be managed however, to improve bulk density and aggregate stability, improving the soil health.

Soil Chemical Component

The chemical components of soil include the pH, nutrients–such as nitrogen (N), phosphorus (P or DAP), potassium (K or potash) –and water. Soil health is critical for determining both the amount of water and nutrients that can be stored in the soil, and the availability of water and nutrients to plants.

The chemical component of soil depends in large part on the soil physical component. Soil physical characteristics determine, in part, how much water the soil can hold. Water fills the spaces, or pores, between the soil mineral particles and is held in the pores by the surface of these particles. Water is held within the pore spaces and on the surface of the particles by two forces. One of the forces is the attractive force between water molecules. The other force is the attractive force between the mineral particle and water. The amount of water that can be held by the soil depends partially on the size of the mineral particles. Smaller mineral particles have greater surface area, smaller pore size, and stronger forces to hold water. The larger the individual pores, the lower the energy of attraction that holds the water within the pore and hence the less water that can be held within the soil. Large soil pores require more energy to hold water within the pore; instead, the water drains out of the soil quickly. As the pores become smaller, the attractive forces between the soil mineral particles and the water increase, holding the water in the pore. For this reason, clay soils, with very small soil particles and small pores, hold more water than sandy soils.

The soil physical characteristics also determine how much water is available to plants. As the soil mineral particles decrease in size, the pore size decreases, binding the water more tightly within the pores. However, while there may be more water in the soil it is no longer available to plants. The water is held so tightly in the pore spaces between the soil particles that plant roots are not able to remove it. Even though there is water in the soil, plants will wilt because of lack of water. The "plant-available water" is an important characteristic of soils that indicates how much water can be stored in the soil and how much of that water is available for the plant roots to take up. For a sandy soil, the large pores in the soil matrix do not hold water easily, limiting the amount of water that can be stored within the soil but making the water that is there readily available to plants. In contrast, a clay soil, with very small pores, can hold more water than sandy soils but the water is not readily available to plants as it is bound tightly within the soil matrix. Clay mineral particles bind water and nutrients very tightly because of the high cohesion, or binding, between the very small clay particles and the water or nutrients. Even when clay soils have high water or nutrient content, the plant may not be able to take up the water and nutrients because the clay particles bind them too tightly.

The soil chemical and physical components depend partially on the mineral elements of the soil, but also on the other components of soil–especially the biological components. The plant roots, soil microbes (bacteria and fungi), and decaying vegetation make up an important part of the soil and help give the soil good structure. A soil with good structure will form stable aggregates that allow easy infiltration of rainwater. The soil aggregates will hold water, yet release the water for greater availability for plants. While tillage initially increases the pore space in the soil, it destroys the soil structure by breaking apart soil aggregates, disrupting plant root and fungal hyphae networks, and reducing organic matter. Tilled soils eventually become more compacted because of this loss in soil structure. In contrast, no-till management preserves the plant and fungal networks, increases the organic matter in the soil, and creates soils with stable aggregates. Organic matter, from plant material and soil organisms, readily absorbs water and holds it until needed by plant roots. More soil organic matter increases the ability of the soil to absorb rain water rather than having it run off. As the organic matter in the soil increases, the plant-available water also increases. It has been estimated that for every 1% increase in soil organic matter, the plant-available water in the soil increases by more than 20,000 gallons per acre (NRCS, 2013; Bryant, 2015). During the rapid growing phase, corn in southeast Kansas uses about ¼ inch of water per day (Figure 4). Every 4 days, a corn crop needs an additional 1 inch of soil water. Soils with greater amounts of organic matter increase both the amount of water held in the soil and the water available to that growing corn crop.

Soil Biological Component

The final component of soil that is critical to the overall productive capacity of soil to provide a "vital living ecosystem" is the biological component. We are learning much more about the factors involved in the biology of soils and their role in soil health. The biological component includes the plants, animals, insects, earthworms, nematodes, arthropods, protozoa, fungi, and bacteria that live in the soil. The biological community is a very important component of soil health. While much of the soil biological community is visible, such as earthworms, much of the biological component is too small to be seen without magnification. This microscopic community, the microbial community or microbiome, is responsible for much of the recycling and transport of nutrients and water that occurs in the soil. A teaspoon of soil can contain a billion bacterial cells, several to hundreds of yards of fungal hyphae (Figure 5), thousands of protozoa, and 10-20 nematodes (Ingham, 2018). Some of these are beneficial, for example the *Rhizobium* bacteria that work with plants to fix nitrogen in legumes such as soybeans. Arbuscular mycorrhizal fungi (AMF) are a group of beneficial fungi that form close bonds with plants, actually growing into the root cells of vascular plants and helping the plants take up nutrients. Other microorganisms are detrimental, such as the fungus *Macrophomina phaseolina* that causes charcoal rot. The soil microbiome is truly a very dynamic, active, and diverse community. The microbial community performs much of the activities of breaking up and recycling plant residues, and capturing nutrients and water. The bacteria and fungi form close interactions with plants, creating symbiotic relationships that benefit both the plants and the microbes. The microbes mine nutrients and water from the soil and transfer these to the plants. In turn, the plants release sugars (carbohydrates) that the microbes need for an energy source. This dense, symbiotic network is the key to soil health.

Soil biological activity is more challenging to measure than physical or chemical properties. Changes in microbial activity have been observed for different production systems (Hsiao et al., 2108), with soils from a hay meadow having nearly 10 times greater microbial biomass than soils from cropped fields. The grasses were also more active deeper in the soil profile, as observed by an increase in enzyme activity within the clay layer (>12 inches depth in the soil profile). By creating dense networks within the soil, grass ecosystems are better able to use more of the soil profile, extracting more nutrients and water for plant growth.

Results and Discussion

We cannot change the mineral composition of soils. We commonly manage the chemical composition through the addition of fertilizers and lime. We can improve the soil biological component through better management practices. Reducing tillage operations will improve soil health by preserving root and fungal networks and increasing the organic matter. This increase in organic matter and biological structure will improve the aggregate stability and productive capacity of the soil. Planting cover crops can also increase the organic matter in the soil. Grasses in particular offer benefits to the traditional prairie soils in southeast Kansas by developing a dense network of roots that grow into the clay layer. By improving the soil health, we can improve the resiliency of our soils–increasing the amount of water stored in the soil, reducing runoff, and increasing the water available for crop production.

Acknowledgment

We gratefully acknowledge the cooperation of the participating farmers in providing us access to their land.

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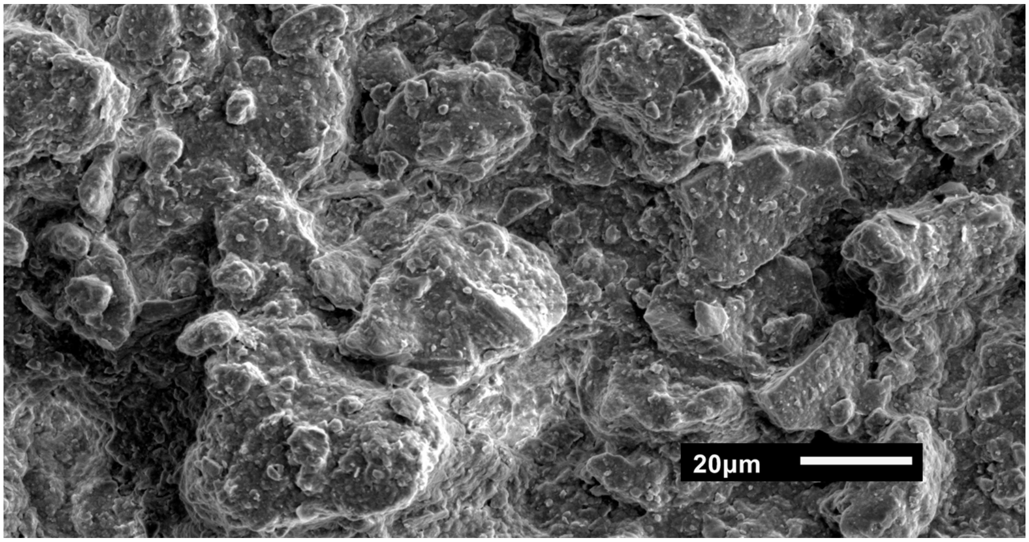

Figure 1. Silt and clay particles in a Kenoma silt loam soil from Labette County, KS. Image magnified 700× with a scanning electron microscope. The white bar is 20 microns in length, roughly equivalent to 0.0008 inches, or about half the thickness of a human hair.

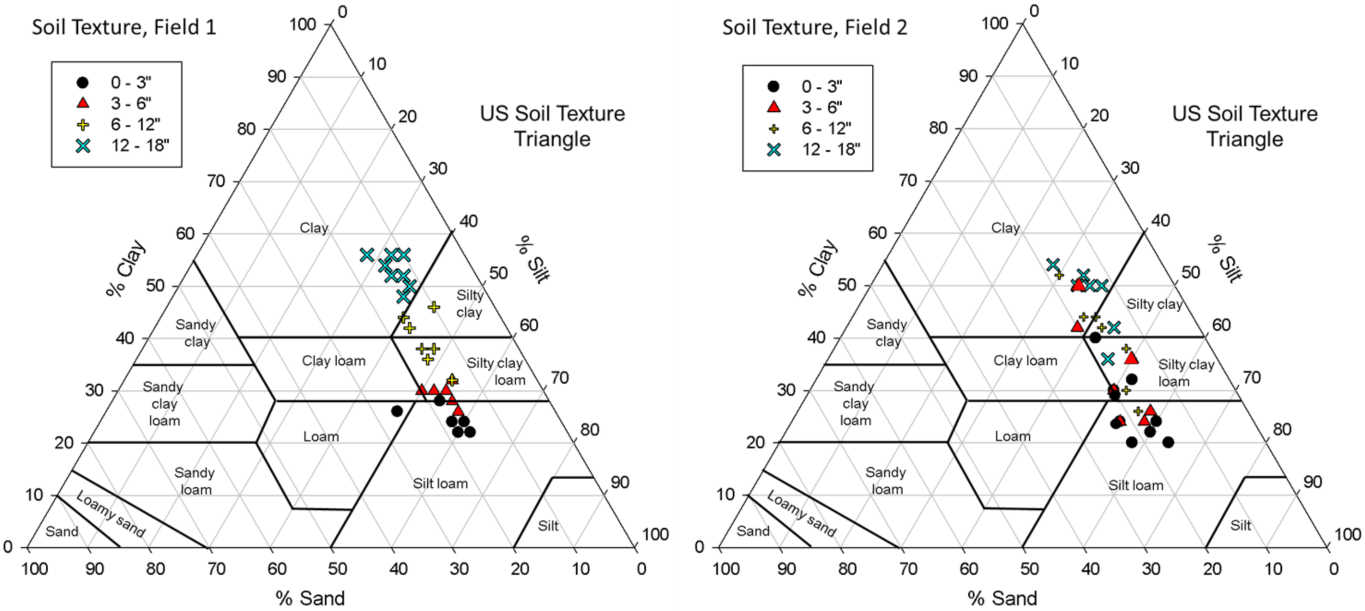

Figure 2. Change in textural classification of soil profiles from two fields in southeast Kansas, based on the US Soil Texture Triangle for composition of sand, silt, and clay. (A) Field 1, with silt loam soil overlying soil with progressively greater percentage clay. (B) Field 2, silt loam topsoil has been lost through erosion, exposing the clay layer at a 3-inch depth at some locations in the field.

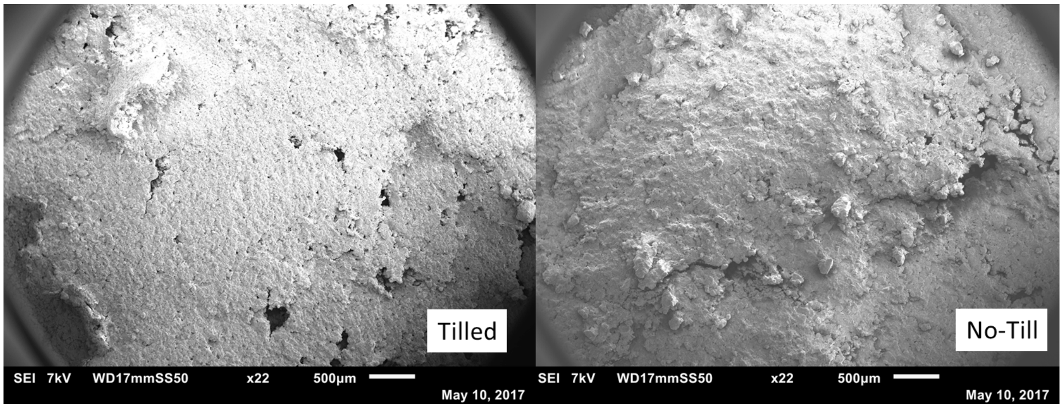

Figure 3. Scanning electron micrograph showing changes in soil structure between tilled and no-till fields for a Kenoma silt loam soil, Labette County, KS.

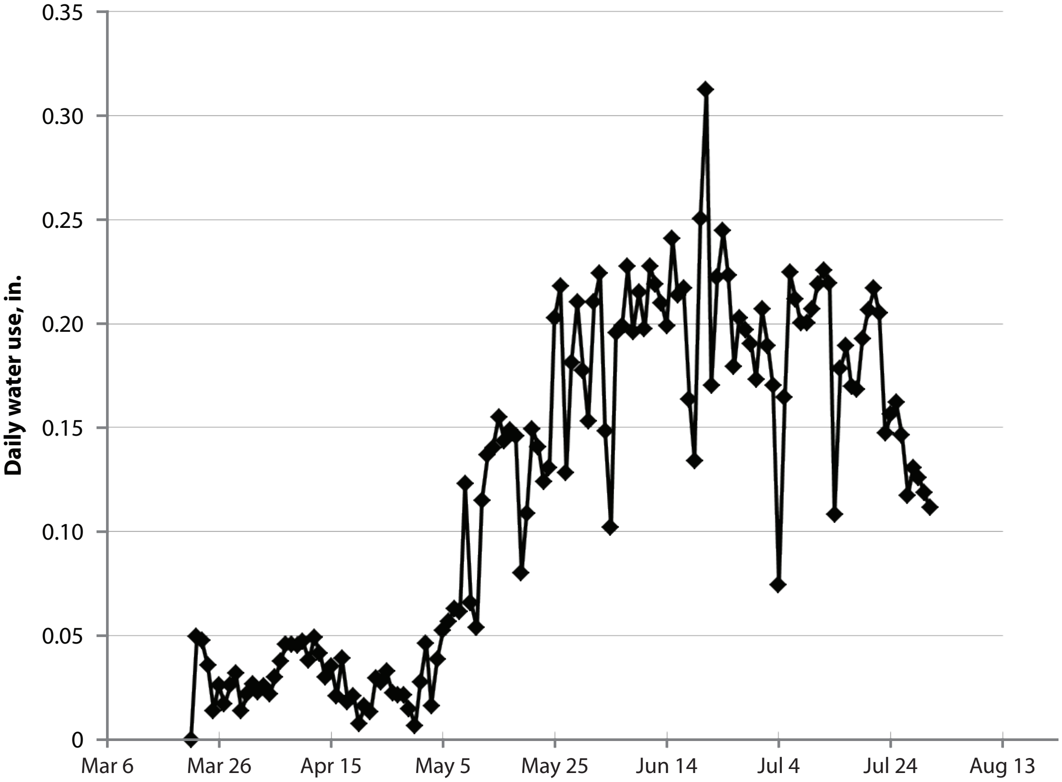

Figure 4. Corn water use calculated based on the Penman-Monteith evapotranspiration equation for a Kenoma silt loam soil in Labette County, KS, 2017.

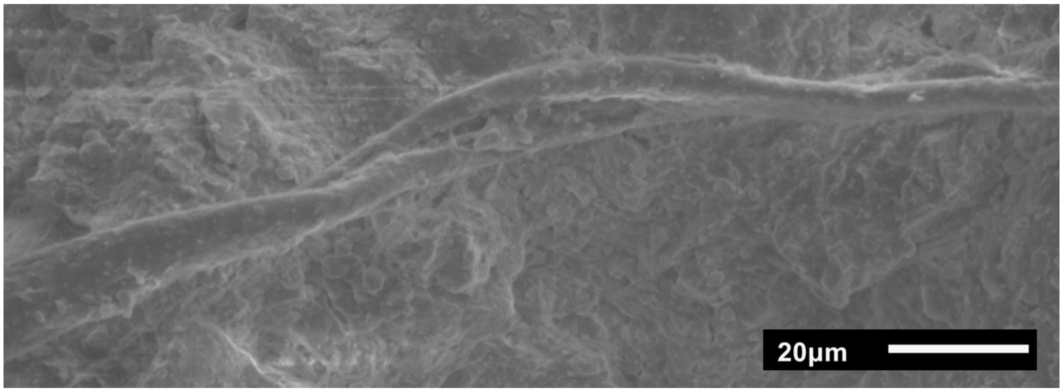

Figure 5. A strand of the microbial network in a Kenoma silt loam soil from Labette County, KS. Image magnified 850× with a scanning electron microscope.