IOWA SOIL HEALTH
Management Manual

IOWA STATE UNIVERSITY
Extension and Outreach

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This soil health management manual provides information about soil functions and services that are essential for sustainable agriculture systems. The research-based information in this soil health management manual highlights the relationships between soil properties that are easy to understand and useful to all, including farmers, agronomists, agricultural consultants, soil scientists, technical service providers, and extension educators.

The soil health management manual has four sections, including:

1. Fundamentals of soil functions and relationships
2. The concept of soil health
3. Management practices that impact soil health
4. Soil health evaluation and procedures indicators

This soil health management manual is the product of the collaborative efforts of Iowa State University and the Department of Natural Resources Conservation Service (NRCS) in Iowa.

1. Fundamentals of Soil Functions and Relationships

Definition of Soil

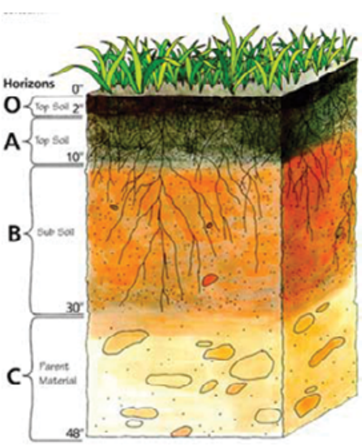
The definition of soil depends on its multiple uses as a medium for different purposes such as farming, engineering, environment, etc.

- A farmer looks at soil as a medium to produce food;
- A geologist views soil as a natural medium;
- An engineer views the soil as unconsolidated materials above the soil bedrock;
- An agronomist or pedologist views soil as a naturally occurring surface layer formed by complex biochemical and physical weathering processes that contain living matter capable of supporting plant, animal, and human life (Brevik, 2005).

As the weathered and fragmented outer layer of the earth's surface, the soil is a nonrenewable natural resource that requires careful management to sustain its vital functions (Eswaran et al., 2001).

Soil Profile and Horizons

The soil profile is the vertical arrangement of distinct horizontal layers called soil horizons from the soil surface to the bottom of a soil pit (Figure 1). The number of horizons in a soil pit depends on the age of the soil; its geographic location, climate, original vegetation where the soil was formed (Hillel, 1998); and



Most soils have three major horizons — the surface horizon (A), the subsoil (B), and the substratum (C).

Some soils have an organic horizon (O) on the surface, but this horizon can also be buried.

The master horizon, E, is used for horizons that have a significant loss of minerals (eluviation).

Hard bedrock, which is not soil, uses the letter R.

FIGURE 1. Soil Profile (Source:www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/edu/kthru6/?cid=nrcs142p2_054308 USDA-NRCS)

Soil Profile (Source: NRCS)

the activities of humans. Younger soils typically have fewer horizons than older soils and each horizon has its unique characteristics that easily identify and distinguish it from other horizons in the same soil profile. Characteristics that can be used to identify and distinguish soil horizons in the same soil profile are the thickness, color, texture, structure, consistency, and pH of that horizon.

Soil horizons are unique to individual soils and are used to identify, classify, and interpret soils. Generally, there are three main horizons in the soil profile, namely A-, B-, and C-horizons (Figure 1). Some soils may have a layer called the O-horizon on top of the A-horizon. The O-horizon, when it occurs as the surface horizon, is the layer of organic matter. The C-horizon is usually called the parent material from which the soil is formed. Further beneath the C-horizon is the bedrock or the R-horizon of the soil profile.

The A-horizon, called the topsoil, is the zone of major biological activity because of its direct contact with the O-horizon at the soil surface. It is the surface mineral horizon that exhibits characteristics like much of the original rock from which the soil developed. It has an accumulation of highly decomposed organic matter mixed with its mineral material and also provides the best environment for the growth of plant roots, soil microorganisms, and other biological life. Over time, the A-horizon loses clay, iron, and other minerals through leaching, a process called **eluviation**. Minerals such as sand that are resistant to weathering tend to remain in the A-horizon as other minerals leach out.

The B-horizon, also called the **subsoil**, is the part of the soil profile with the greatest accumulation of chemicals that have leached from the A-horizon (a process called **illuviation**). The B-horizon is also a mineral horizon with more clay but lower in organic matter content than the A-horizon. The A and B soil horizons together are called the soil **solum** where most plant roots grow (Richter and Yaalon, 2012; Cline, 1961). Some soils may also have E-horizons between the A- and B-horizons. If the E-horizon exists in the soil profile, it loses the clay minerals, iron, and aluminum that have leached from the A-horizon into the B-horizon. Therefore, E-horizons in the soil solum are typically lighter in color because of the loss of clay minerals and oxides of iron and aluminum. The set of soil horizons from the soil surface to the bottom of the soil pit is called the **soil profile**.

Composition of Soil

Soil has three major components including the **solid**, **liquid**, and **gaseous** phases (Figure 2).

SOLID PHASE

The solid phase of soil is approximately 50 percent of the total soil volume, consisting of 45 percent **mineral particles** called the **primary separates component of the soil** and approximately five percent **soil organic matter** depending on the soil type, which is influenced by parent materials, vegetation, climate, and human activity. (Figure 2).

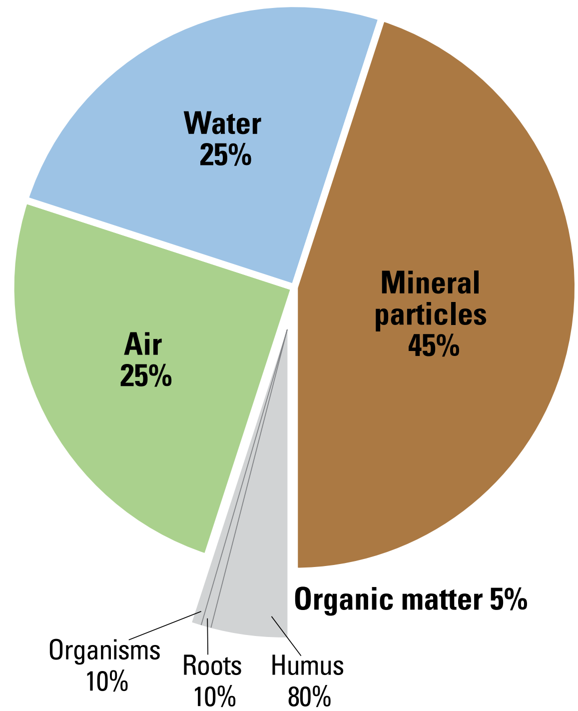


FIGURE 2. Soil Composition (Source: Pidwirny, 2006)

SOIL ORGANIC MATTER

Soil organic matter (SOM) consists of all the organic components of the soil (Figure 3), which include decomposed and decomposing **plant residue, dead and living plant roots, worms, ants**, and **other insects, snails,** and all **soil microorganisms**, including **fungi, bacteria, viruses,** and **nematodes**. Organic matter influences the biological and chemical properties of the soil and plays a significant role in building soil structure. The type of vegetation in a location influences the organic matter quality and quantity and microbial biodiversity of the soil in that location.

FIGURE 3. Soil organic materials Source: Justin Evertson (2013). "Living Soils Sustain Landscapes" from "Beneficial Landscapes: the plants, wildlife, soil, and water for our gardens"

SOIL MINERAL COMPONENT

This component of soil is the combination of different proportions of the mineral particles of **sand, silt,** and **clay** (Figure 4), giving rise to the three broad categories of soil texture (Table 1), namely sandy, clayey, and loamy soils (Brady and Weil, 1999). In any given amount of soil, the proportions of sand, silt, and clay particles add up to 100 percent. The combination of different portions of silt, sand, and clay determine what is called **"soil texture,"** which influences soil porosity, soil hydraulic properties, and soil chemical properties. The following are major categories of the soil texture of mineral soils.

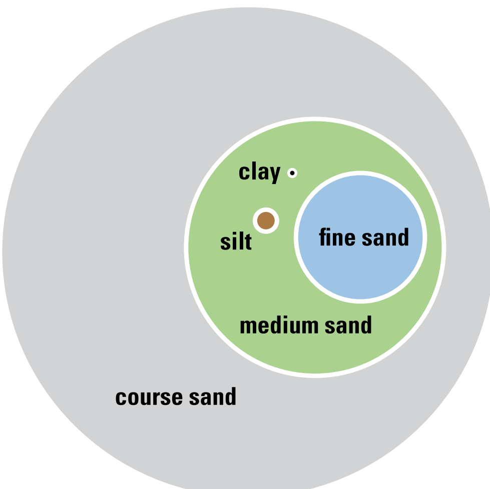


FIGURE 4. Mineral composition of the soil Source: (Whiting et al., 2014)

TABLE 1. General terms used to describe soil texture in relation to the basic textural class names

Common names	Texture	Basic soil textural class names
Sandy soils	Coarse	Sands Loamy sands
	Moderately coarse	Sandy loam Fine sandy loam
Loamy soils	Medium	Very fine sandy loam Loam Silty loam Silt
	Moderately fine	Sandy clay loam Silty clay loam Clay loam
Clayey soils	Fine	Sandy clay Silty clay Clay

Source: The nature and properties of soils, 12th Edition, page 125

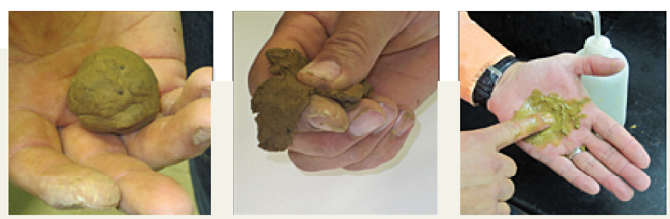
SOIL TEXTURAL CLASSIFICATION

Sandy soils

Sandy soils have the largest particle sizes among the three primary soil minerals (Figure 4). Individual sand particles range in diameter from 0.078 to 0.002 inches (Brady and Weil, 1999). Sandy soils are coarse in texture and feel gritty to the touch. They cannot hold water because water drains easily and rapidly through the large pore spaces between the sand particles. Sandy soils can be worked easily and warm up quickly in the spring. To test for sandy soils by feel, moisten the soil and try to roll it in the palm. Sandy soils do not form balls in the palm and easily crumble through the fingers (Figures 5 and 6).

Silt soils

Silt soils have much smaller particle sizes with particle size diameter in the range of 0.002 to 0.00008 inches compared to sand (Figure 4). Silt soils form soil surface crust under dry conditions. To test for silty soils by feel, moisten the soil and rub it with the fingers. Silty soil particles are smooth to the touch and feel slick and soapy when wet (Figures 5 and 6).



STEP 1: Start with a small handful of soil, about the size of a golf ball, and slowly add water a drop at a time, mixing as you go, until you have a ball of soil that has the consistency of putty. Gently squeeze the ball to determine if it will stay together in a ball or fall apart.

STEP 2: If the ball of soil stays intact, gently press the ball between your thumb and index finger, trying to work out to form a ribbon. If you can form a ribbon, measure how long the ribbon is before it falls apart.

STEP 3: After completing the ribbon test, add water to a pinch of soil in the palm of your hand until you have a muddy puddle. Rub the mud puddle against your palm and determine if it feels gritty, smooth, or equally gritty and smooth.

FIGURE 5. Three simple steps to determine soil texture by feel (Source: Ritchey et al., 2015)

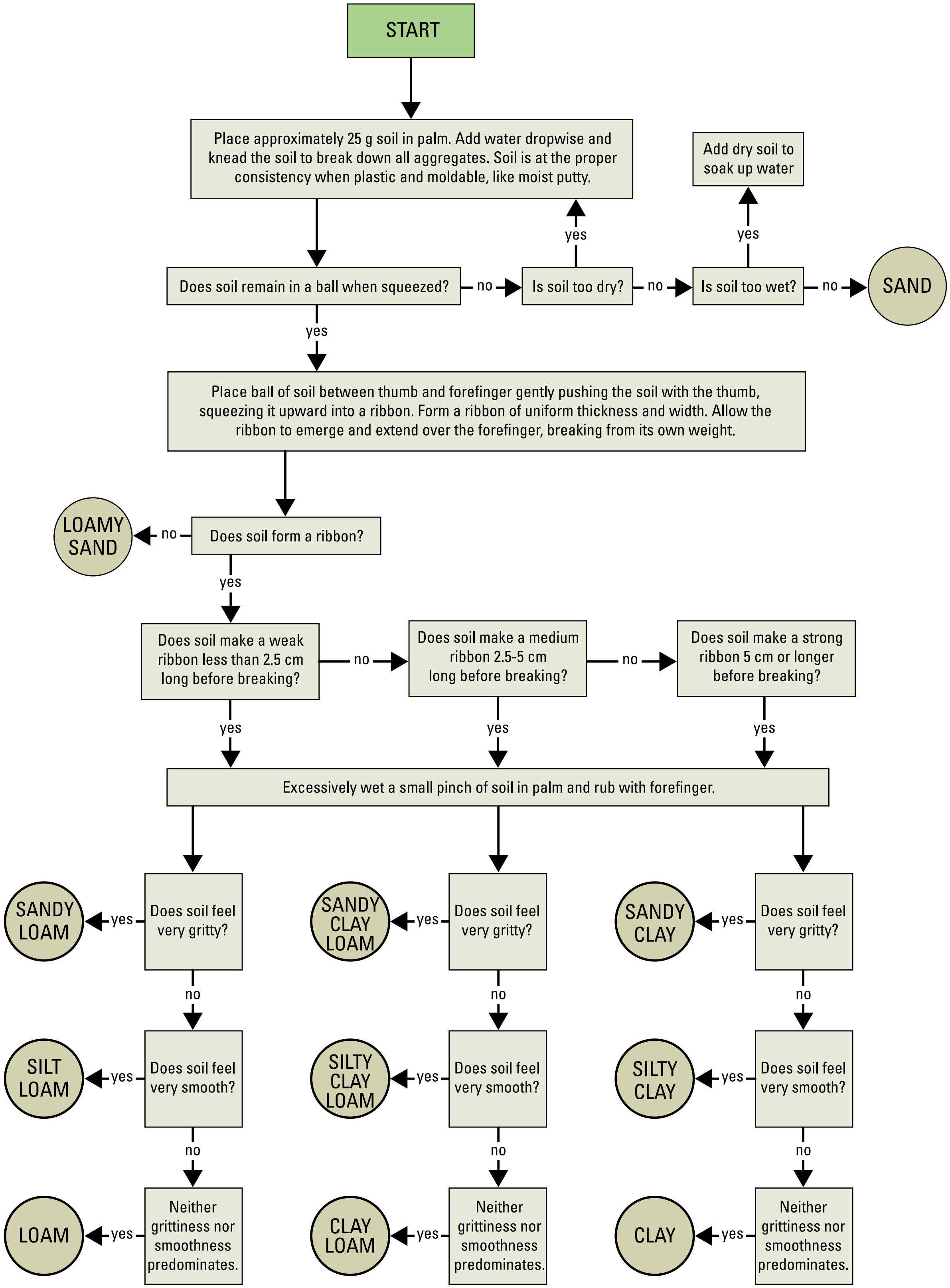


FIGURE 6. A flow diagram for teaching texture by feel analysis. Source: USDA-NRCS Guide to texture by feel. Modified from S. J. Thien, 1979

Clay soils

Clay soils have the finest particles among the three soil mineral particles (Figure 4) with particle sizes smaller than 0.00008 inches in diameter. Clay soils have good water storage qualities because of the very fine pore spaces between the particles. Clay soils are smooth when dry and stick like glue to shoes and garden or farm tools when wet. During dry weather clay soils become very hard and difficult to work. To test for clay soil by feel, moisten the soil and try to roll it into a ball in the palm. Clay soils will roll easily into balls or form a sausage-like shape in the hand when wet (Figures 5 and 6).

The different portions of sand, silt, and clay particles form different classes of soil textures with distinct soil physical and chemical properties that influence the soil environment, which includes soil moisture availability, drainage, nutrient availability, microbial activities, and organic compounds. Examples of different soil texture classes are summarized in Table 2. One of the tools used to determine soil texture is the USDA soil textural triangle chart (Figure 7). The following text is the procedure for using the USDA textural triangle chart.

TABLE 2. Guide for judging how much moisture is available for crops according to soil texture

Available Soil Water	Medium (Coarse) Texture	Medium (Fine) Texture	Fine and Very Fine Texture
100 percent soil moisture	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand 1.8 inch/foot	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand 2.2 inch/foot	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand 2.0 inch/foot
75 percent available soil moisture remaining	Forms a ball, is pliable 1.35 inch/foot (0.5 inch/foot)	Forms a ball, is pliable, sticks readily 1.65 inch/foot (0.55 inch/foot)	Easily ribbons out between fingers, sticks 1.50 inch/foot (0.5 inch/fto)
50 percent available moisture remaining	Forms a ball, somewhat plastic 0.9 inch/foot	Forms a ball, somewhat plastic, will stick slightly with pressure 1.1 inch/foot	Forms a ball, ribbons out between thumb and forefinger 1 inch/foot

Source: Al-Kaisi, 2000. Iowa State University Extension Publication ICM News, IC-484(6)—April 24, 2000

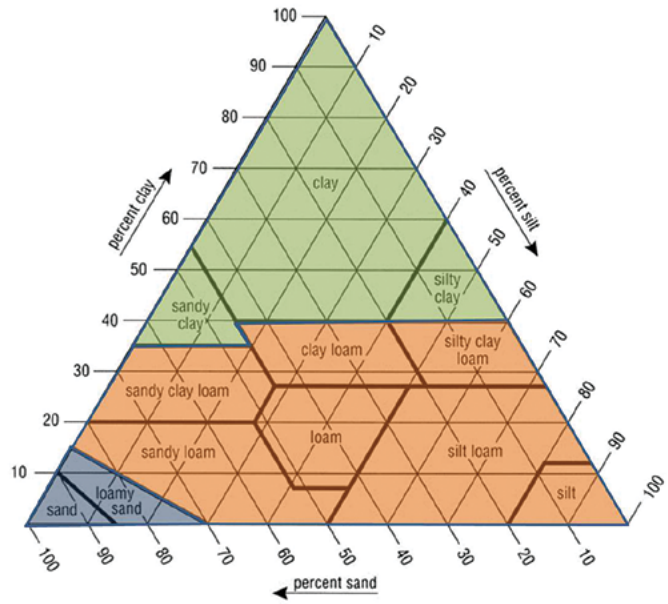


FIGURE 7. Mineral composition of the soil. Source: University of Minnesota Extension, adapted from NCRS, www.extension.umn.edu/garden/yard-garden/trees-shrubs/selecting-shrubs-for-minnesota-landscapes/

How to Use the USDA Soil Textural Triangle

In order to classify a given soil by its texture using the USDA soil textural triangle chart, find the point of intersection of the lines drawn from the sides of the triangle that represent the percentage of the primary separates (sand, silt, or clay) in the soil. The sum of the percentages of all the mineral particles add up to 100 percent and the point of intersection of the lines identifies the textural class of the soil.

In the USDA soil textural triangle chart, the right and left sides of the textural triangle represent the respective percentages of silt and clay in the soil. The base of the triangle represents the percentage of sand in the soil.

For example, assume a soil has 55 percent sand, 15 percent silt, and 30 percent clay. In order to determine the textural class of the soil, locate the percentage of sand at the base of the triangle and draw a line upwards parallel to the right side of the triangle (silt). Next, locate the percentage of silt on the right side of the triangle and draw a line downward toward the base of the triangle parallel to the left side of the triangle (clay). Subsequently, locate the percentage of clay on the left side of the triangle and draw a line parallel to the base of the triangle (sand) and determine the point of intersection of the three lines you drew on the textural triangle chart (Figure 8). The point of intersection of the three lines will represent the texture of that particular soil, according to the USDA.

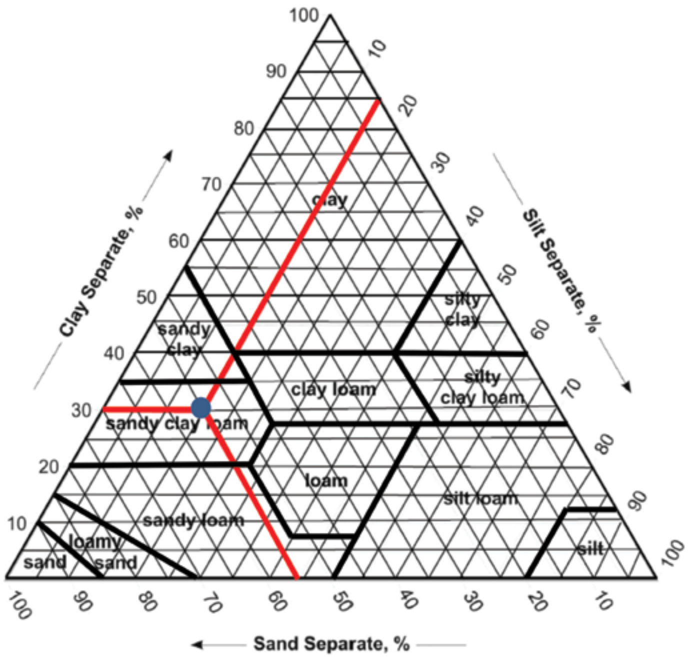


FIGURE 8. Example for determining point of intersection of three red lines showing the percentages of sand (55%), silt (15%) and clay (30%) particles in a sandy clay loam soil on the USDA soil textural triangle chart. (Source: Emerson, 2015)

Using the above percentages of sand, silt, and clay, a person can determine the point of intersection of the lines, which in this case is in the **sandy clay loam** section on the triangle (Figure 8) and is the class of the soil texture (**sandy clay loam**).

How to Determine Soil Texture

The following is a simple way to determine the proportions of sand, silt, and clay in your soil sample (Whiting et al., 2014).

1. Spread the soil on a newspaper to dry. Remove all rocks, roots, and any trash and crush lumps and clods.
2. Finely pulverize the soil.
3. Fill a tall slender jar (like a quart jar) one-quarter full of soil (Figure 9).
4. Add water until the jar is three-quarters full.
5. Add a teaspoon of powdered, non-foaming dishwasher detergent.
6. Place a tight fitting lid on the jar and shake hard for 10 to 15 minutes to break aggregates.
7. Set the jar where it will not be disturbed for the next 2 to 3 days.
8. Observe that soil particles will settle out according to size with the largest particles settling to the bottom. **One minute** after setting down the jar after shaking, mark on the jar the height of the large particles (**sand**) at the bottom.
9. After **2 hours**, mark on the jar the depth of the medium-size particles (**silt**).
10. **When the water clears**, mark on the jar the depth of the small particles (**clay**) between the clear water and the silt. This typically takes 1 to 3 days, but with some soils it may take weeks.
11. Measure the thickness of the sand, silt, and clay layers marked on the jar.
12. Add all the measured values and consider that value as 100 percent.
13. Calculate the percentages of the sand, silt, and clay from the 100 percent.
14. Follow the example in Figure 8 to determine the textural class of the soil.

Soil Structure

Soil structure is the arrangement of individual soil particles (sand, silt, and clay) into secondary particles or groups (Figure 9) called **aggregates** that are held together by organic matter and mineral oxides (Tisdall and Oades, 1984) in the horizon of the soil profile. The number of horizons in a soil profile (Figure 1) depends on the location and the factors of soil formation. However, soil aggregates only occur in the A-, E-, and B-horizons with the aggregates separated by planes of weakness. Therefore soil structure is one of the defining characteristics of soil horizons.

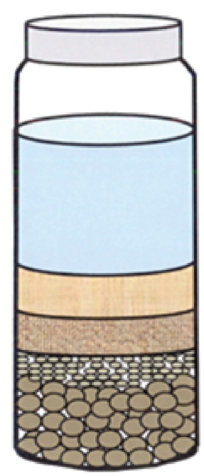


FIGURE 9. Soil texture by measurement: Measure the depth of the sand, silt, and clay. Source: Estimating soil texture: Sand, silt, or clayey (Whiting et al., 2014)

Classification of soil structure

Soil structure has been classified in a number of ways depending on the bonding of individual soil particles within or between aggregates or the shapes of the soil aggregates. Based on bonding within or between the aggregates, soil structure may be classified as structureless, weak, moderate, or strong. Based on shape of soil aggregates, soil structure may be classified as granular, prismatic, massive, small grain, blocky, or platy (Figure 10).

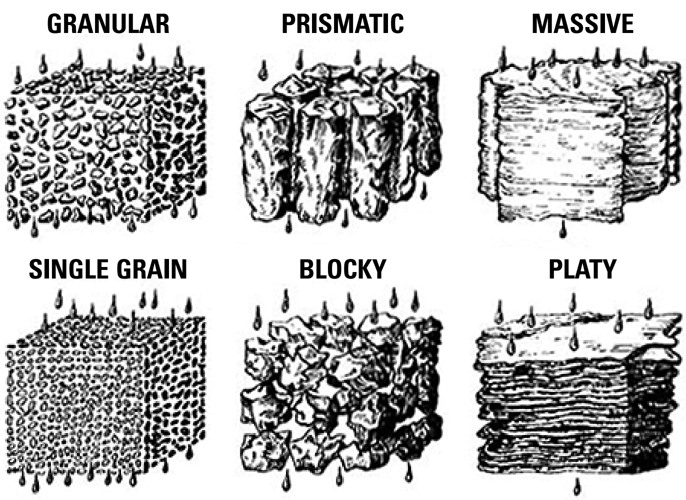


FIGURE 10. Examples of different soil structure types. Source: Managing soil tilth (Whiting et al., 2014)

The soil structure determines soil porosity and the depth of plant roots in the soil profile. Soil structure also determines how easily soil air and water can flow in the soil profile for root respiration and nutrient absorption by plants.

Soil porosity

Soil porosity represents 50 percent of the total soil volume and is the void space in the soil that can be filled by air and water. Soil porosity therefore influences soil bulk density, whereby less porous soils have higher bulk densities compared with more porous soils. The porosity of soils generally varies with soil particle sizes and soil aggregation. A volume of clay or organic soil with smaller particle sizes is more porous than the same volume of a sandy soil. The higher number of smaller

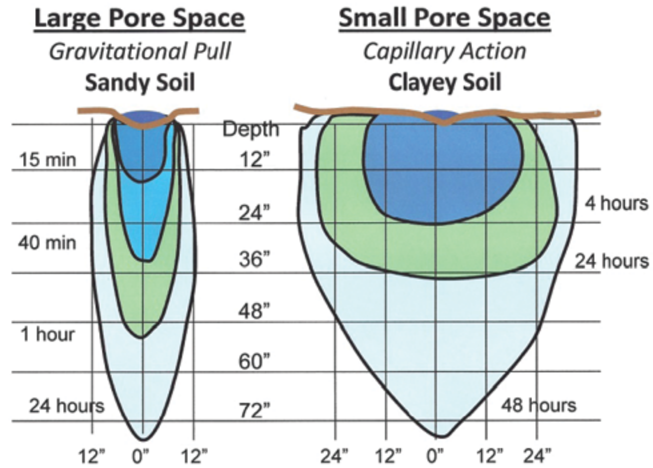


FIGURE 11. Comparative movement of water in sandy and clayey soil. Source: (Whiting et al., 2014)

particles in the clay or organic soil produces a higher total volume of soil pores. On the other hand, the fewer and larger particles of the sandy soil occupy the same volume with fewer pores as depicted by the period of time it takes water to flow through clay and sandy soils (Figure 11). The ability of soils to hold and allow water to move through the soil depends on the sizes and number of pores, which also depends on the texture and structure of the soil.

LIQUID PHASE

The liquid phase of soil or the soil solution is soil water with dissolved plant nutrients. Figure 12 shows how soil solution moves into the root of plants based on the energy of soil water, which determines how free soil water can move in the soil (McElrone, 2013). The amount of water in the soil and its energy are important factors that affect plant growth (Hillel, 1998). The ability of water to freely move through the soil profile depends on the energy of soil water also called the **soil water potential**. Soil particles are collectively called the **soil matrix**. When the force of attraction between the soil matrix, also called the **soil matric potential**, and soil water is low, soil water potential is high and soil water easily moves in the soil to drier areas. When soil matrix potential is high, it means the soil is dry with restricted soil water movement in the soil.

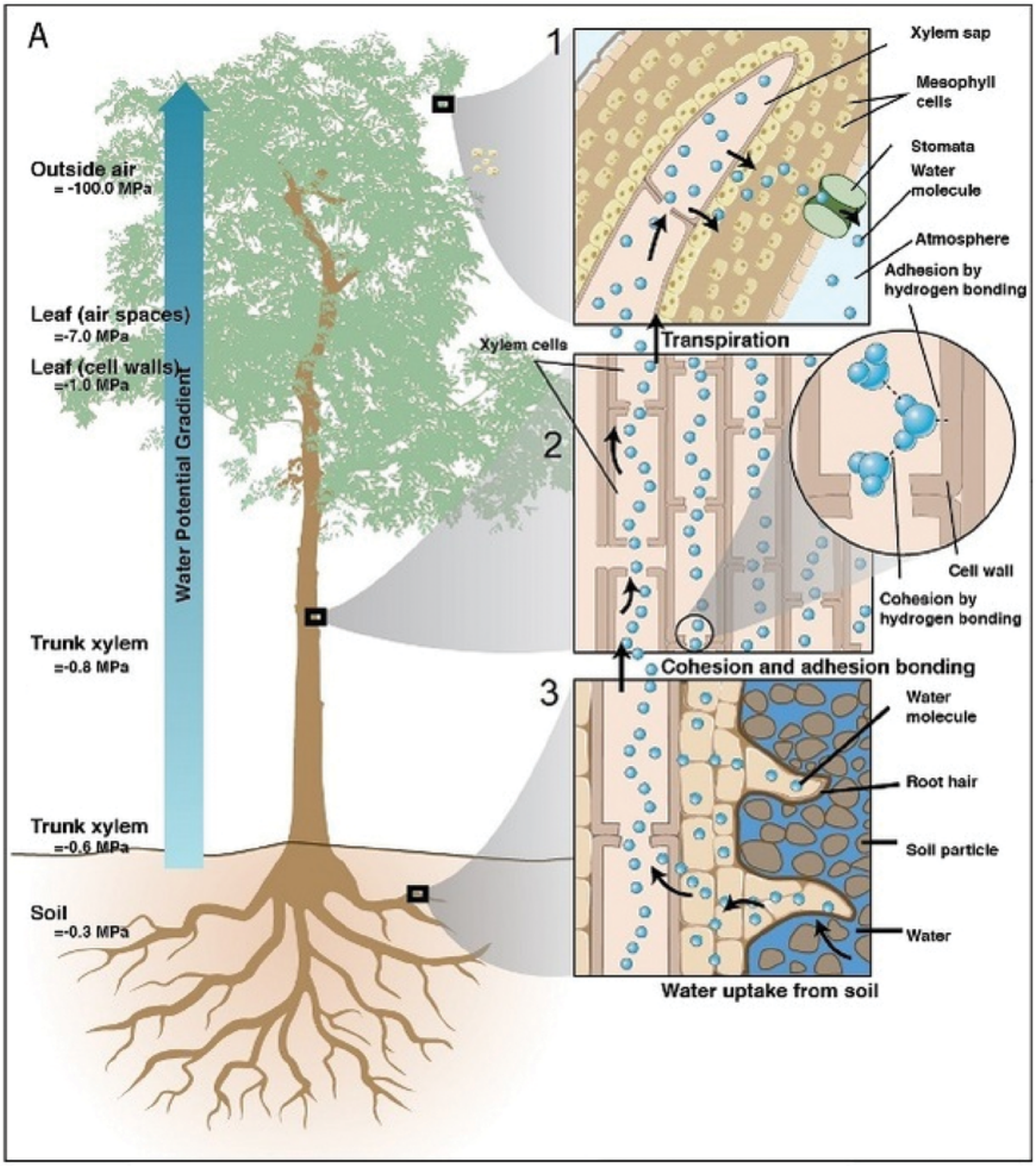


FIGURE 12. Water movement from the soil into the plant root (Source: McElrone et al., 2013). Illustration © 2013 Nature Education. All rights reserved.

SOIL WATER TERMS AND RELATIONSHIPS

As explained in the previous paragraph, water movement in soil is controlled by the **soil water potential** and the **matric potential**. However, another factor, the **osmotic potential**, also affects soil water movement. Soil water is in the form of a solution because of dissolved salts and nutrients. The attraction between soil water and its dissolved salts or soil nutrients is the **osmotic potential**, which has a negative value and always reduces the energy with which soil water moves in the soil. When the concentration of salts and nutrients in the soil increases from fertilizer application, the osmotic potential of the soil solution increases and further restricts soil water movement. Also, when the soil gets drier, osmotic potential increases because of the reduction in the amount of water in the soil compared to the concentration of salts and nutrients; and coupled with the force of attraction between water and the soil matrix, soil water potential becomes more negative with very little energy to move in the soil (Figure 13). When the soil is saturated with water, water moves in the soil by the **force of gravity.** Therefore the three factors that influence soil water movement are the **gravitational potential**, **matric potential**, and **osmotic potential**.

GRAVITATIONAL POTENTIAL

Gravitational potential is the energy of soil water when its movement is influenced by the force of gravity. This occurs when the soil is completely saturated with water, especially after a heavy rainfall or irrigation event. Under saturated soil conditions the soil pores are completely filled with water and no air; the only force that influences soil water movement under saturated conditions is the force of gravity, which pulls soil water downward to lower soil depths and into tile drains (Figure 13).

MATRIC POTENTIAL

Matric potential is the force of attraction between the surfaces of soil particles and soil water. When the soil is dry, matric potential is higher, and lower when the soil is wet. When the soil is not saturated, water moves only from wet to dry areas in the soil, supplying water and nutrients to plant roots from different directions in the soil profile.

OSMOTIC POTENTIAL

Osmotic potential results from dissolved salts and nutrients (e.g., fertilizers) in soil water. When fertilizer is applied to the soil it dissolves in the soil water to form a solution and also increases the concentration of salts and nutrients in the solution, which makes soil water less available to plants. This creates a concentration gradient in the soil solution such that soil water in areas of lesser concentration of salts and nutrients flows to the area with a higher concentration of the salts and nutrients. The force that drives soil water from areas of lower concentration of the solution to areas of higher concentration is the osmotic potential. When the high concentration of nutrients in close proximity to the root system is high, it allows the dissolved nutrients to flow into the root system, thus creating a lower concentration of the soil solution around the root zone. This in turn allows more soil solution to flow toward the root zone to replenish the nutrients absorbed into the roots.

SOIL WATER AVAILABILITY

In the soil, different moisture conditions such as drought and wet events affect soil water availability, which is also influenced by soil texture. The three soil water conditions that describe the different forms of available soil water are **soil saturation**, **field capacity**, and **permanent wilting point**.

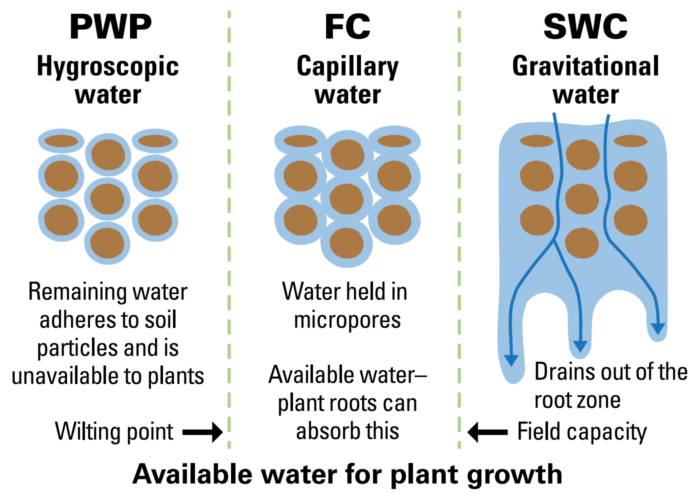


FIGURE 13. Schematic representation of different soil water limits (Source: USDA-NRCS)

SOIL SATURATION

Soil saturation is the condition of the soil when all its pores both large (**macro-pores**) and small (**micro-pores**) are completely filled with water. At this condition, the soil has no air, and soil water has greatest energy to move. The energy of soil water at soil saturation is zero (0 bars) and flows only under the pull of gravity, especially as it occurs in fields with tile drains during heavy rain events. When soil water drains freely under the force of gravity, it drains only from the macro-pores and that soil water is called **gravitational water** or **Saturated Water Condition (SWC)**. Gravitational water is not absorbed by plants because it drains beyond the root zone (Figure 13). This kind of condition can lead to nutrient loss beyond the root zone (**leaching**), especially soil nitrate.

FIELD CAPACITY (FC)

Field capacity is the condition of the soil after gravitational water has stopped draining from the soil and the macro-pores are filled with air. Therefore soil water at field capacity is only held in the micro-pores of the soil. The energy of soil water at field capacity is **0.3 bar**, which makes soil water readily and easily available to the plant to absorb. Because soil water at field capacity is held in the micro-pores, which form tiny capillary tubes, it is called **capillary water** and only moves upwards through the capillary tubes by a process called **capillary action**. Capillary water at field capacity is easily absorbed by plant roots because it is not strongly held to the surfaces of the soil particles (Figures 13 and 14).

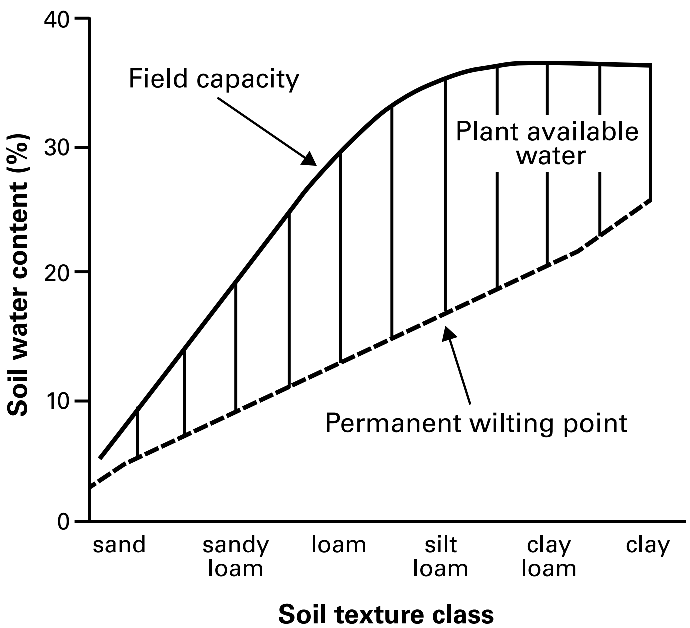


FIGURE 14. Plant available water. (Source: O'Green, 2012)

PERMANENT WILTING POINT (PWP)

Permanent wilting point is soil water condition under extreme dry conditions, when soil water is below the field capacity and the soil micro-pores are filled with air. At the permanent wilting point, there is only a thin film of soil water on the surfaces of the soil particles, which cannot be absorbed by plant roots because it is held at a pressure equal to **-15 bars**. When soil water is at such a condition, plants experience permanent damage to their tissues unless there is immediate rain or irrigation. Soil water at the permanent wilting point is called **hygroscopic water** (Figures 13 and 14).

PLANT AVAILABLE WATER (PAW)

Plant available water is the amount of soil water held between **field capacity** and the **permanent wilting point** (Figures 13 and 14). It is called plant available water because it is soil water with nutrients for growth that plants can absorb. Different soil textures have different amounts of plant available water (Figure 14). Loamy soils hold more plant available water than pure sand and clay soils.

MEASUREMENT OF SOIL WATER CONTENT

There are a number of ways to measure soil water content. Among these are those primarily used in research, including the use of electrical resistance blocks, watermark blocks, the gamma-ray absorption method, and the use of time-domain reflectometry (TDR) methods. These methods provide information that is essential for water management, especially with irrigated agriculture. Most of these methods are affected by soil conditions such as soil texture, salt concentration, and the requirement for equipment calibration.

On the other hand, soil water measurement methods such as the gravimetric and hand-feel methods are not expensive, not sophisticated, and very practical for use by farmers to accurately determine soil water content. Of the two, the hand-feel method can be used on the spot in the field with accuracy.

HAND-FEEL METHOD

The hand-feel method for determining soil water content in the field is qualitative and faster. However, it depends on experience, is subjective, and prone to error. The hand-feel method requires only a handful of soil for every one foot of soil depth across the active root zone in the soil profile. The only equipment required for this method is a soil probe, an auger, or a shovel to extract the soil samples.

Soils have different texture; therefore, soil texture plays a significant role in the hand-feel method for soil water determination with regard to soil consistency, the formation of shapes, and traces of soil moisture on the hand.

Typically, soil sampling for this method is done in 1-foot (30 centimeter) increments to the root depth of the crop. The following are the steps to follow for the hand-feel method.

1. Collect soil samples using a soil probe, an auger, or a shovel.
2. Squeeze a handful of the soil sample firmly in your hand several times to form an irregularly shaped "ball."
3. Squeeze the soil sample out of your hand between your thumb and your forefinger to form a ribbon.
4. Observe soil texture, ability to form a ribbon, firmness, surface roughness of ball, water glistering, loose soil particles, soil/water stains on fingers, and soil color (Figures 5 and 6).
5. Consult Table 2 to determine how much soil water is available for crops according to soil texture.

THE GRAVIMETRIC METHOD

This method for determining soil water content is quantitative, reliable, and simple, but can be labor intensive and requires time. The method requires using a soil probe, an auger, or a shovel to extract the soil from a known soil depth. The wet weight of the soil sample is determined by weighing the sample as it is at the time of sampling. To obtain the dry weight of the soil sample, place the sample in an oven at 105°C in an aluminum can and allow drying to a constant weight, for 24 hours. An ordinary household microwave oven can also be used for drying the soil sample (place soil in a nonmetal, microwave safe container). Allow the oven-dry soil sample to cool before weighing. The amount of water in the soil sample, also called the **mass wetness** or the **gravimetric wetness**, is determined as the ratio of **weight of water** in the wet soil to the **weight of the oven-dried soil**.

Calculations

To determine the gravimetric water content (G) of the soil based on dry weight basis, divide the weight of water (W_m) in the soil sample by the oven-dry weight of the soil sample (S_{dm}).

Weight of soil water (W_m) = Weight of wet soil (S_{wm}) – Weight of oven-dry soil (S_{dm})

Then $G = (\frac{W_m}{S_{dm}} \times 100)$ = % of water content.

To express the gravimetric water content on volume basis use the following formula:

Volumetric soil water (%) = $\frac{W_m}{S_{dm}} \times \rho_b \, 100\%$, where ρ_b is bulk density.

Example of Gravimetric Soil Water Content Calculation

Measurements	Weight (grams)
Weight of can, W_c	24.42 grams
Weight of can + wet soil, W_{c+s}	194.54 grams
Weight of Wet soil, S_{wm}	170.12 grams
Weight of can + dry soil, W_{c+sdm}	177.52 grams
Weight of dry soil, S_{dm}	153.10 grams
Weight of water, W_m	170.12-153.10 = 17.02 grams
Gravimetric Water, G	17.02 grams/153.10 grams = 0.11116
Percent Gravimetric Water (%)	0.11116 x 100 = 11.12%

GASEOUS PHASE

The gaseous phase of the soil is the air-filled and water vapor pore space of the soil medium, which is a continuation of the air in the atmosphere. Soil air is in constant circulation with the air of the atmosphere, which results in the addition of fresh air from the atmosphere to the soil, a process called **soil aeration**.

COMPOSITION OF SOIL AIR

Soil air is a mixture of gases, which include nitrogen, oxygen, carbon dioxide, and water vapor. The source of oxygen, nitrogen, and carbon dioxide in soil air is the atmosphere. However, part of the carbon dioxide in soil air comes from root respiration and the decomposition of organic matter in the soil. The nitrogen content of soil air (79.2 percent) is 0.7 percent lower than the nitrogen content (79.9 percent) of air in the atmosphere. The oxygen content of soil air (20.6 percent) is 1.8 percent lower than the oxygen in the atmosphere (20.97 percent) and the carbon dioxide in soil air (0.3 percent) is 10 times higher than the carbon dioxide (0.03 percent) in the atmosphere (Russel and Appleyard, 1915).

Determining soil air composition

FACTORS THAT AFFECT THE COMPOSITION OF SOIL AIR

Factors that affect the composition of soil air include the nature and condition of the soil, type of vegetation/crop and microbial activities in the soil, and seasonal variation.

Soil Condition, Crop and Microbial Activities in the Soil

The amount of oxygen in soil air depends on the degree of soil wetness and varies with soil depth. Wetter soils have lesser amounts of oxygen in the soil air because of the presence of much water in the soil and a smaller amount of air in the soil pores. At lower soil depths, the amount of oxygen in soil air decreases. This is because air in the topsoil layers readily circulates with the air in the atmosphere (Hillel, 1998). Generally, the carbon dioxide content of soil air is higher than that of the atmosphere. However, at lower soil depths carbon dioxide in soil air is highest because of root respiration and poor aeration of subsoils.

Plant roots get oxygen for respiration from soil air, and in the process, deplete the amount of oxygen in the soil. Therefore, soils with actively growing plants contain lesser amounts of oxygen than soils without actively growing plants.

Soil microorganisms are responsible for organic matter decomposition in the soil, but also require oxygen for respiration. As soil microorganisms deplete the oxygen in soil, they increase the amount of carbon dioxide in soil by respiration and organic matter decomposition. Therefore, soils richer in organic carbon have a higher concentration of carbon dioxide because of microbial respiration and organic matter decomposition.

Seasonal Variation

Seasonal variations affect the composition of soil air. During the growing season when plants are actively growing in the field, soil air has less oxygen and a high concentration of carbon dioxide because of root respiration and soil microbial activities. During winter, cold air and soil temperatures slow down soil microbial activity and air circulation between the soil and the atmosphere. This reduces the amount of oxygen and carbon dioxide in soil air compared to the growing season. During spring and summer as soils warm up and become drier, there is increased soil microbial activity and air circulation between the soil and the atmosphere, especially during summer and that leads to soil aeration with more oxygen in the soil. Also, higher air and soil temperatures during summer increases soil microbial activity, thereby increasing the carbon dioxide content of soil air.

2. The Soil Health Concept

Definition of Soil Health

Soil health is defined as *"the continued capacity of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health."*

The concept of soil health also means healthy soils have the ability to sustain plant and animal life and productivity, as well as soil biodiversity; maintain or enhance water and air quality; and support human health and wildlife habitat.

Foundation of Soil Health

The foundation of soil health is **soil biodiversity**, which consists of all the biological components of the soil including plant roots, earthworms, bacteria, fungi, actinomycetes, algae, protozoa, nematodes, mites, springtails, and small insects. Soil biodiversity plays a significant role in building soil aggregates (groups of primary soil particles—sand, silt, and clay) that are held together by organic compounds and mineral oxides as essential components of a healthy soil.

MECHANISM OF AGGREGATE FORMATION AND BENEFITS

Substances that bind soil particles together into soil aggregates are from inorganic and organic sources. However, from the standpoint of soil health, the most essential substance known to bind primary soil particles into aggregates is **glomalin** (Figure 15). Glomalin is the glue-like substance secreted by the hyphae of a group of soil microorganisms called **arbuscular mycorrhizal fungi** (AMF). The hyphae of AMF are thread-like structures through which nutrients and water enter plant roots (Figure 16). The hyphae of AMF grow beyond nutrient depleted zones found around roots and root hairs and form a frame for soil particles to collect into aggregates coated with glomalin. When glomalin binds with iron or other heavy metals, it can keep carbon from decomposing. Even without heavy metals, glomalin stores carbon in the inner recesses of soil particles where only slow-acting microbes live. This carbon in organic matter is also saved like a slow-release fertilizer for later use by plants and hyphae.

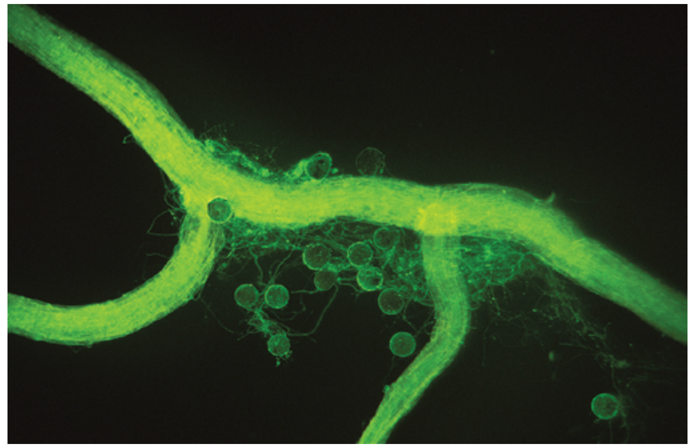


FIGURE 15. A microscopic view of an arbuscular mycorrhizal fungus growing on a corn root. The round bodies are spores, and the threadlike filaments are hyphae. The substance coating them is glomalin, revealed by a green dye tagged to an antibody against glomalin. Credit: Photo by Sara Wright. Source: www.ars.usda.gov/is/graphics/photos/sep02/k9968-1.htm

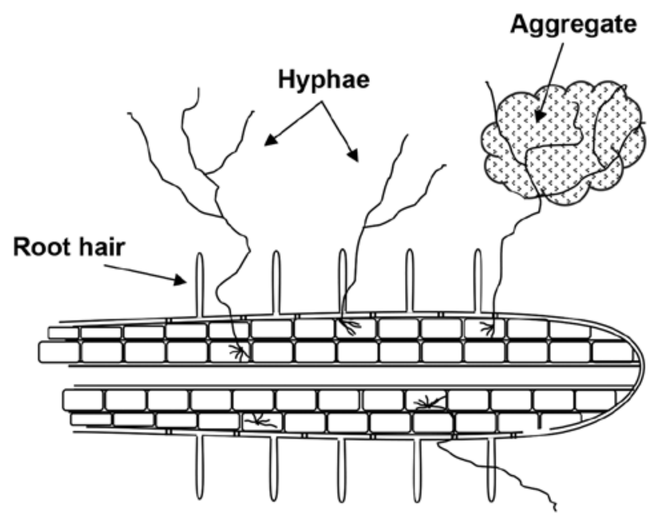


FIGURE 16. Hyphae of arbuscular mycorrhizal fungi on roots and root hairs. (Source: Nichols, www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1144429.pdf)

Characteristics of a Healthy Soil

The characteristics of a healthy soil are related to the **stable** or **inherent** and **dynamic** properties of the soil.

INHERENT SOIL PROPERTIES

Inherent (Static) Soil Properties are associated with the process of soil formation and influenced by parent materials, vegetation, climate, time, and topography.

These properties define soil's natural ability to function. These soil properties include soil texture, depth to bedrock, drainage class, and cation exchange capacity (CEC). Some of these inherent properties, such as CEC, can be influenced by other properties such as type and content of clay and soil organic matter (SOM) content because the increase in both increases CEC.

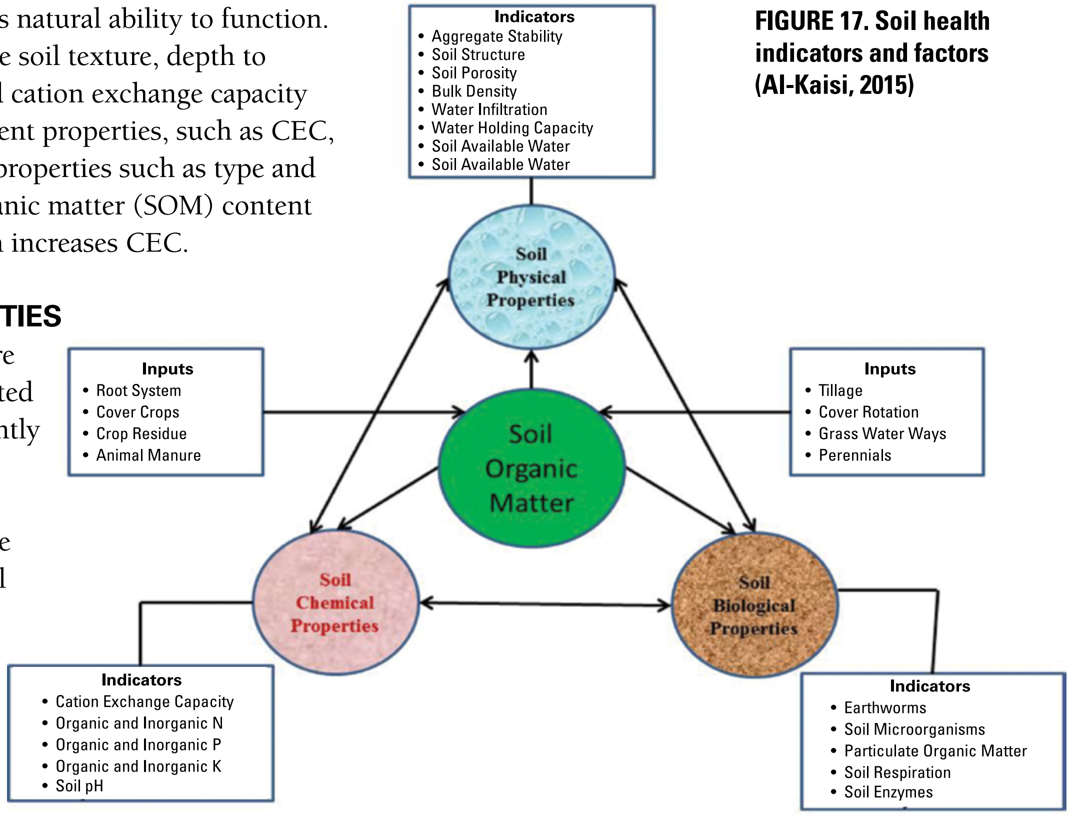


FIGURE 17. Soil health indicators and factors (Al-Kaisi, 2015)

DYNAMIC SOIL PROPERTIES

Dynamic soil properties are soil properties that are affected by management and constantly changing either with or without human activities within a short period of time or in the long-term. The soil properties are soil organic matter (SOM), microbial community, bulk density, infiltration rate, soil water, and nutrient holding capacity.

SOIL HEALTH INDICATORS

Unlike the inherent properties of the soil, the dynamic soil properties are all affected by land management practices including soil tillage, cropping systems, and other land use practices. Therefore, the focus of soil health indicators is on the **dynamic soil properties** and how those properties change in relation to the **inherent properties** to keep the soil healthy (Figures 17 and 18). The inherent and dynamic properties of soils are used as indicators to evaluate soil health based on the three broad categories of **physical**, **chemical**, and **biological** properties of the soil.

SOIL PHYSICAL PROPERTIES

Generally, the physical properties of soil show how well the soil can provide physical stability and support for plants and soil organisms. The physical properties of soil also show the relationships between soil-water, air, and plant. The following are some soil physical properties that can be evaluated to determine the level of soil health and functionality: bulk density, aggregate stability, water infiltration rate, field capacity, and plant available water (Figure 17).

Soil Bulk Density

Soil bulk density is a measure of porosity expressed as the amount of solid soil particle weight per volume of such mass and defined as gram per cubic

Effect of soil compaction on root and seedling growth at three different soil bulk densities: Low, 0.7 grams/cm^3; Medium, 1.1 grams/cm^3; High, 1.6 grams/cm^3 (Al-Kaisi, 2006)

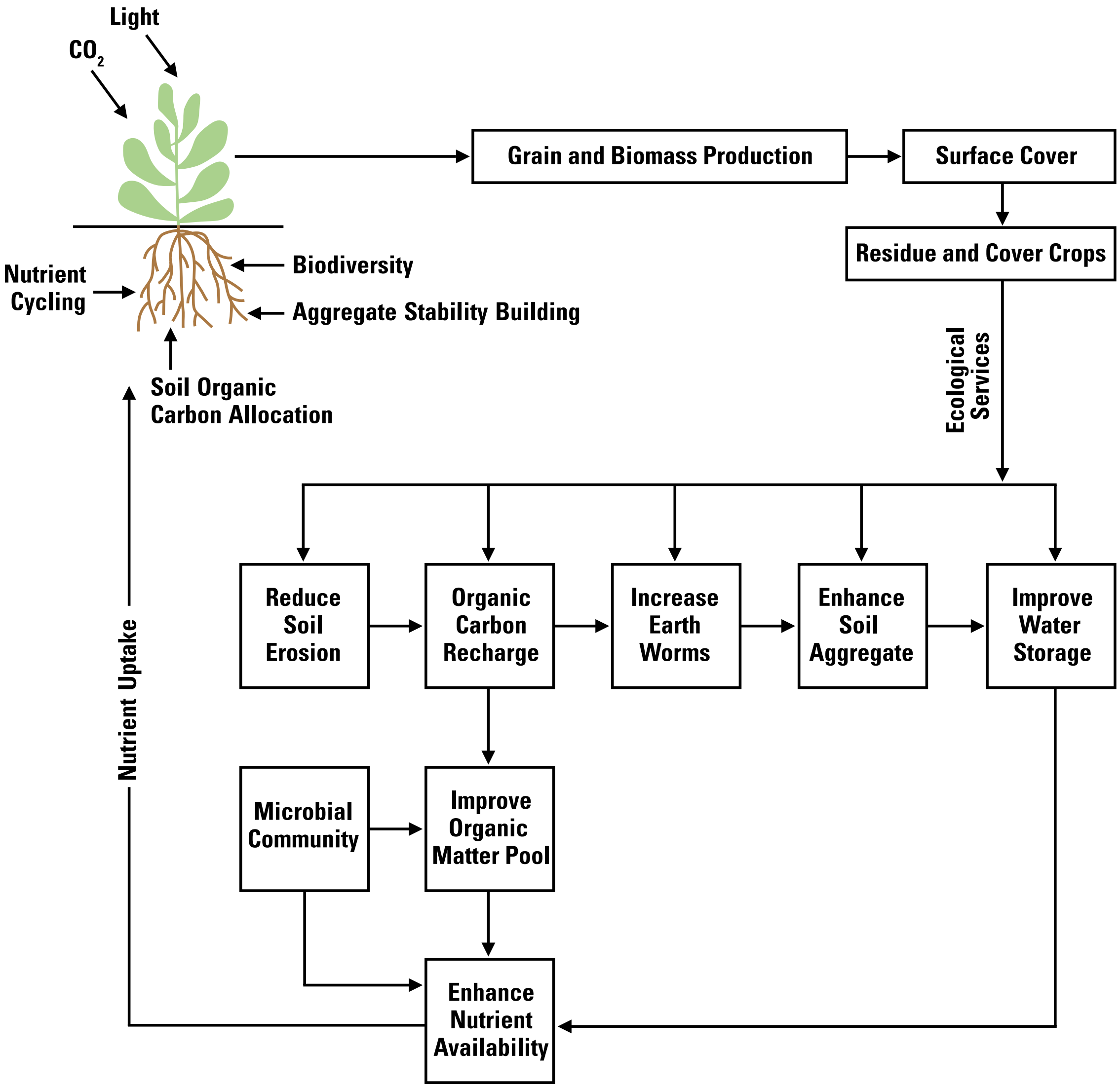


FIGURE 18. Crop residue and cover crops for improving soil health functions and nutrient cycling (Al-Kaisi, 2015)

centimeter (/cm^3). Soil bulk density is an important soil health indicator, because it reflects the level of porosity and compaction in the soil. Compacted soils have less porosity, lower air content, lower water infiltration rate, restrictive root growth, and poor plant growth compared to a non-compacted soil. Table 3 shows bulk density values for different soil textures that are ideal for, or restrictive of plant root growth. Management practices

TABLE 3. General relationship of soil bulk density to root growth based on soil texture

Soil Texture	Ideal bulk densities for plant growth (grams/cm^3)	Bulk densities that affect root growth (grams/cm^3)	Bulk densities that restrict root growth (grams/cm^3)
Sands, loamy sands	< 1.60	1.69	> 1.80
Sand loams, loams	< 1.40	1.63	>1.80
Sandy clay loams, clay loams	< 1.40	1.60	> 1.75
Silts, silt loams	<1.40	1.60	>1.75
Silt loams, silty clay loams	<1.40	1.55	>1.65
Sandy clays, silty clays, clay loams	<1.10	1.49	>1.58
Clays (>45% clay)	<1.10	1.39	>1.47

Source: USDA-NRCS Soil Quality Kit-Guides for Educators 2014. (http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053260.pdf) that result in higher bulk density involve conventional tillage and mono-cropping systems, overgrazing with livestock, burning and removal of crop residue, and random equipment traffic, especially on wet soils.

Soil Aggregate Stability

Soil aggregate stability means the ability of soil to strongly bind together and withstand the force or pressure applied by rain intensity and traffic. It is another way to describe the strength of the soil structure to resist the impact of any external force or pressure, especially rainfall. Healthy soils should have stable soil aggregates capable of resisting the destructive impact of rainfall and water and wind erosion. Soil aggregate stability is affected by soil **texture**, **type of clay**, **extractable cations,** the amount of organic matter, and the **type and population of soil microorganisms** present in the soil. **Soil tillage destroys the stability of soil aggregates.**

Water Infiltration

Water infiltration is the movement of water through the soil surface into the soil profile. The rate of infiltration is relative to the rate of rain intensity or water supplied to the soil surface, which influences how much water will enter the root zone and how much will run off the soil surface. Soil texture, soil structure (bulk density and aggregate stability), and slope impact water infiltration rate of soils the most, especially pore size distribution and the continuity of pores.

Measuring water infiltration

Determining infiltration in the field

Conventional tillage practices can reduce water infiltration significantly, because of the destruction of soil structure as shown in Figure 19. Management practices—such as no-tillage or strip-tillage—improve water infiltration, increase water recharge, and reduce water runoff. Runoff is the major contributor to nutrients and sediment loss, and water quality deterioration. Field measurements and observation of water infiltration can be achieved by using a simple ring method or water conditions after rain events as a reflection of management effects on soil health.

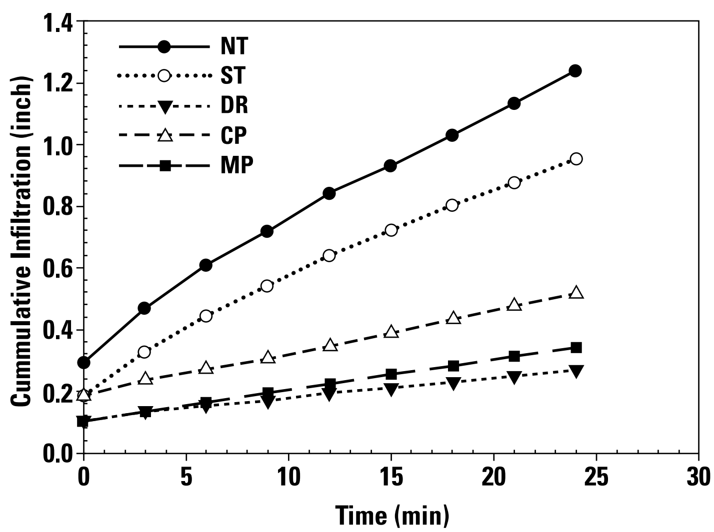


FIGURE 19. Cumulative water infiltration in different tillage systems. NT=no-till; ST=strip-tillage; CP=chisel plow; DR=deep rip; MP=moldboard plow (Al-Kaisi, 2015)

Measuring soil surface moisture

Field Capacity

Field capacity (FC) of a soil is the amount of water or moisture content held in soil after excess or free water has drained downward to lower depths. Soil at FC provides the optimal condition of water and air for plant growth. After a rain or irrigation event, any excess or free water (saturation condition) in the soil drains by gravity to lower soil depths. The amount of water that remains in the soil is easily available to plants.

Plant Available Water

Plant available water (PAW) is defined as the difference between soil water or moisture content at field capacity (optimal moisture condition) and the permanent wilting point (PWP); the driest soil condition where soil water is not available to plants. The plant available water is highly influenced by soil texture. Loam textured soils have a higher amount of plant available water compared to clay textured soils.

SOIL BIOLOGICAL PROPERTIES

Soil biology plays an important role in building soil health, facilitating soil organic matter decomposition and nutrient cycling, and the release of macro-nutrients such as nitrogen (N) and phosphorus (P), and secondary and micronutrients that plants can absorb to grow. The process of converting organic N into inorganic N by soil microorganisms is called **nitrogen mineralization**, which is part of the nitrogen cycle as shown in Figure 20. In the nitrogen cycle, soil bacteria play a vital role in breaking organic N to NH_4^+ and NO_3^- that will be available for plant uptake.

The decomposition of organic materials in the soil by microorganism ultimately produces humus, the most stable organic matter that helps build soil structure (i.e., soil aggregates) and a nutrients pool. A large diverse population of soil microorganisms also competes with disease-causing organisms in the soil to reduce their numbers. Soil organisms, like earthworms, play an important role in building soil tilth. Earthworms provide rich source (castings) of nutrients by the breakdown of plant materials in their digestive system. Also, they create channels that aid in the redistribution of nutrients in the soil profile.

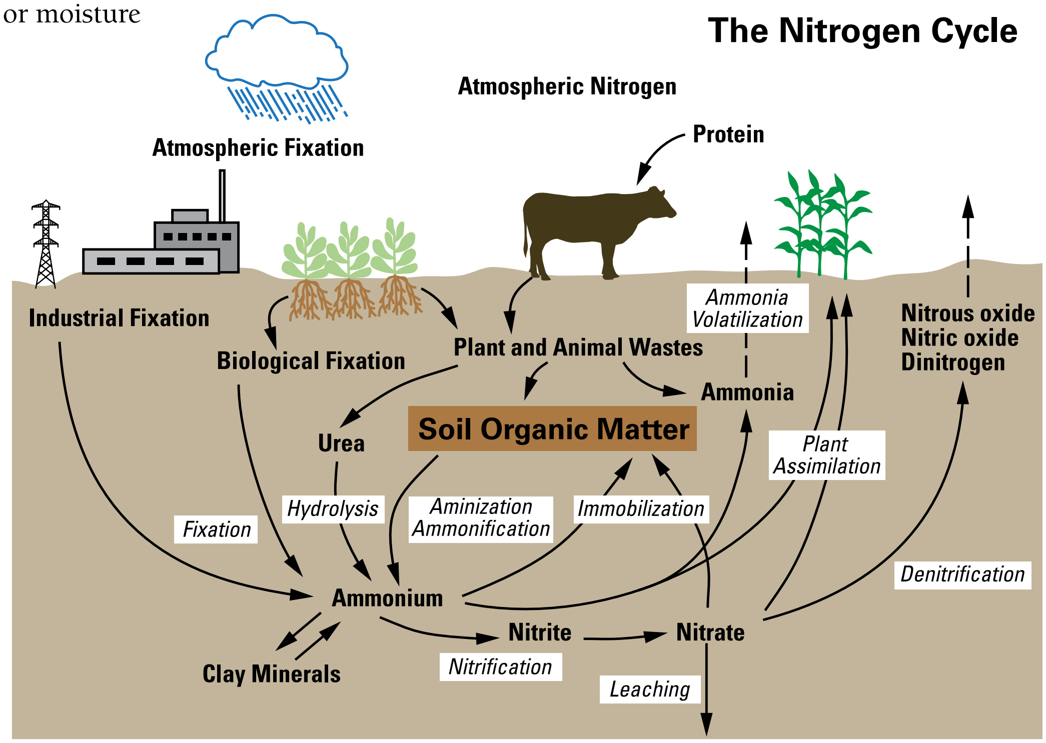


Figure 20. The nitrogen cycle. ("Soil as a Plant Sees It," University of Nebraska–Lincoln, 1991)

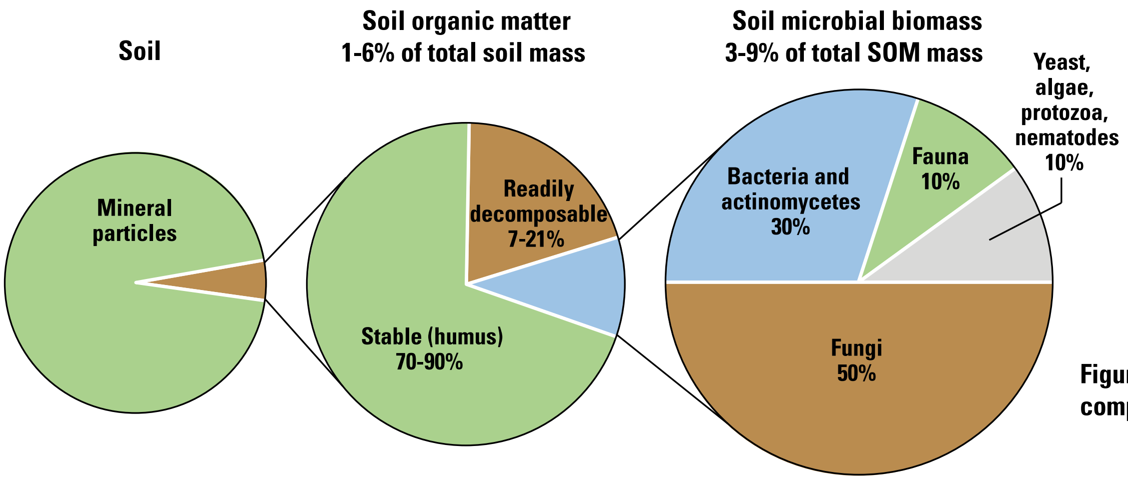


Figure 21. Organic matter composition

Soil Organic Matter

Soil organic matter (SOM) is the single most important soil health factor because it affects the soil's physical, chemical, and biological properties. Soil organic matter, which constitutes 1 to 6 percent of the total soil mass depending on soil forming conditions, may include:

- 7 to 21 percent of readily decomposable organic matter;
- 3 to 9 percent of soil microbial biomass (which includes 30 percent bacteria and actinomycetes, 10 percent fauna, 10 percent yeast, algae, protozoa, nematodes, and 50 percent fungi); and
- 70 to 90 percent of stable soil organic carbon (humus).

The unique benefits of soil organic matter for soil health include:

- Increasing soil fertility by retaining positively charged elements called cations.
- Conserving soil nutrients in their organic forms to slowly be released in the soil as condition becomes optimum (moisture and temperature).
- Producing hormones that help plants to grow.
- Providing food for soil microorganisms.
- Binding soil particles together into aggregates that improve soil structure, water, and air movement.
- Improving soil water holding capacity for plant use and cation exchange capacity.

Decomposition of soil organic matter can be rapid or slow depending on its chemical structure. Starches and proteins decompose faster than cellulose, fats, waxes, resins, and lignin. Soil organic matter that has completely decomposed is called humus. About 70 to 90 percent of the non-living part of soil organic matter is humus. Soil organic matter is the source of the soil nutrients, such as nitrogen (N), phosphorus (P), and sulfur (S), which are released into the soil during decomposition.

Conventional tillage is a major factor in destroying soil organic matter by accelerating the oxidation of organic matter as shown in Figure 22. Tillage operation increases soil aeration, which can increase microbial activity to decompose organic matter in the soil.

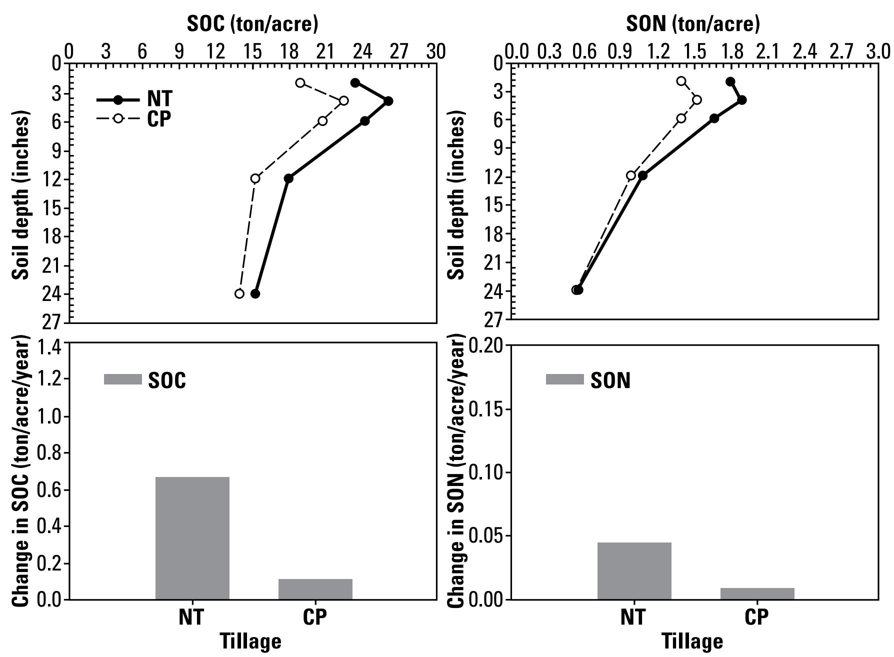


Figure 22. Tillage effects on soil organic carbon inputs from crop residue. NT = no tillage and CP = chisel plow (Al-Kaisi, 2005)

Other Biological Indicators to evaluate soil biological activities may include microbial biomass carbon (MBC), rate of CO_2 evolution or respiration, phospholipids fatty acids (PLFA), earthworm population, soil organic carbon (SOC) concentration, and enzyme concentrations in soil. These are properties that can be evaluated in the laboratory using procedures that are specific to each one. The overarching property and most important in evaluating soil biological health is the determination of soil organic matter as the precursor for a healthy soil environment. These indicators are sensitive to management practices such as tillage and cropping systems.

SOIL CHEMICAL PROPERTIES

Soil chemical properties are essential for well-functioning soils to support the growth and functions of plant and soil organisms. In the soil a number of inorganic and organic chemical reactions and processes take place that are essential for soil productivity and plant growth including cations and anions exchanges and base saturation, which is the portion of cation exchange capacity (CEC) occupied by bases. These chemical reactions and processes in the soil are controlled by clay minerals, oxides and hydroxides of iron and aluminum, and humus. The following are soil chemical factors or properties that affect the soil environment: soil pH, CEC, and the soil nutrient pool.

Soil pH

Soil pH is the measure of the level of soil acidity or alkalinity based on amount (concentration) of free hydrogen ions (H+) in the soil (Figure 23). When the concentration of hydrogen ions in the soil is high,the pH of the soil is acidic. Alkaline soils have low concentration of hydrogen ions. Soil pH is measured on a scale of 0 to 14. Soil pH value of 7 is neutral. Soil pH is acidic when the value is lower than 7 and alkaline or basic when the value is higher than 7.

Soil pH is important because it directly affects **soil fertility**. Many annual crops grow best when the soil pH is close to neutral in the range of 6 to 7.5. However, when the soil becomes acidic from farming practices, including excess fertilizer application, it affects nutrient availability. Lime application is the recommended management practice to correct the acidic soil condition.

Cation Exchange Capacity

Cation exchange capacity (CEC) is the ability of the soil to hold nutrients (cations) and release them during chemical reactions for plant uptake. In the soil, a number of cations including calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and others contribute to soil fertility. These cations are held by the negatively charged surfaces of the clay minerals and organic matter (humus) in the soil.

The CEC values depend on soil texture, clay type and amount, soil pH, and organic matter content. Soils with higher clay and organic matter content will have higher CEC. Therefore, managing soils for high crop yields and residue input, including soil pH and nutrient supply, will help to maintain or increase soil CEC.

Soil Nutrient Pool

The **soil nutrient pool** is simply the reservoir of nutrients in the soil, which is generally reported in mass or weight of the nutrient per unit area of soil as pounds per acre (lb/acre). The primary nutrient pools of the soil include:

- Soil organic matter and compounds that provide nutrients through mineralization process.
- The soil solution (water with dissolved nutrients).

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Optimum for most crops								■							
Drained bogs containing sulfur		■	■												
Humid forest soils					■	■	■								
Sub humid grassland soils															
Semiarid grassland soils							■	■	■						
Soils containing excess Ca^{2+} salts									■						
Soils containing excess Na^+									■	■	■				

Figure 23. Typical pH ranges for various types of soils (Source: Troeh and Thompson, 1993 in Smith and Doran, 1996)

- Exchangeable positively charged elements (cations) and negatively charged elements (anions).
- Bonding of cations and anions with the mineral surfaces of the soil.
- Primary and secondary minerals as a result of chemical reaction process in soil.

Soil health is directly linked to soil fertility, which depends on the amount and availability of nutrients in the soil nutrient pools. Soil organic matter is one of the major sources of nutrients released into the soil system from plant uptake. The availability of plant nutrients from these different pools varies greatly. Plant materials such as cover crop, crop residues, fine root turnover, and manure inputs can help boost some of these nutrient pools.

Understanding the Carbon to Nitrogen (C:N) Ratio

Soil microorganisms use the carbon (C) and nitrogen (N) in crop residue for energy and building new tissue, respectively. The ratio of the amounts of carbon and nitrogen (C:N ratio) in the crop residue left in the field plays a significant role in how fast the residue breaks down and adds organic carbon and nitrogen into the soil. Therefore, a basic understanding of the concept of C:N ratio is essential for practical farming.

When organic matter breaks down in the field, it may result in the net release of nitrogen (N) into the soil; this process is called **mineralization or N release**. When the residue decomposition results in an N deficit without any release of N into the soil, the process is called **immobilization** or **tied-up**. With immobilization, soil microorganisms utilize all the N in the residue to form new tissue, in which case the N is not immediately available to plants for use. Therefore, whether residue decomposition results in mineralization (release) or immobilization (tied-up or no-release), will depend on the **C:N ratio** of the plant material added to the soil. Plant materials with high C:N ratio, such as corn (75:1), will have a slow decomposition process, whereas plants with low C:N ratio (35:1), such as soybean residue, will have a much faster decomposition. The optimal C:N ratio for soil microbes to decompose plant materials is less than 20:1.

How to Determine Residue Decomposition

Example of Residue Breakdown:
A farmer leaves 4400 pounds of crop residue on his field after harvest, which contains 55% carbon with a C:N ratio of 20:1. Will residue decomposition result in mineralization or immobilization?

Solution: Step 1
Determine the amount of carbon (C) by weight present in the crop residue left in the field as follows:
4400 pounds × 55% = 2420 pounds

Step 2
Determine the amount of nitrogen (N) present in the residue based on the [C over N] ratio of 20:1 as follows:

$$\frac{C}{N} = \frac{20}{1} = \frac{2420\ lb}{N}, \frac{2420\ lb}{20} = 121\ lb \text{ of organic N.}$$

Step 3
Calculate the amount of carbon (C) and nitrogen (N) needed by soil microorganisms to form new tissues: During residue decomposition, soil microorganisms will decompose 0.75 or 75% of total carbon (C). 0.25 or 25% will be used by the microbes to build new tissue. This amount is: 0.25 × 2420 *lb* = 605 pounds of carbon used by the microorganisms.

To build new tissue, soil microorganisms need on average $\frac{C}{N}$ ratio 8:1

Therefore, the amount of N required by soil microorganisms to form new tissue will be

$$\frac{605}{8} = 75.63 \text{ pounds of N.}$$

Step 4
Finally, compare the original amount of N in the residue, in step 2, (121 *lb* of N) and the amount of N from the residue used by the soil microorganisms (76 pounds of N).

There is a **net positive balance** of 45 pounds N, (121-76 = 45 *lb*) released into the soil that may be available to plants and this means **N mineralization**.

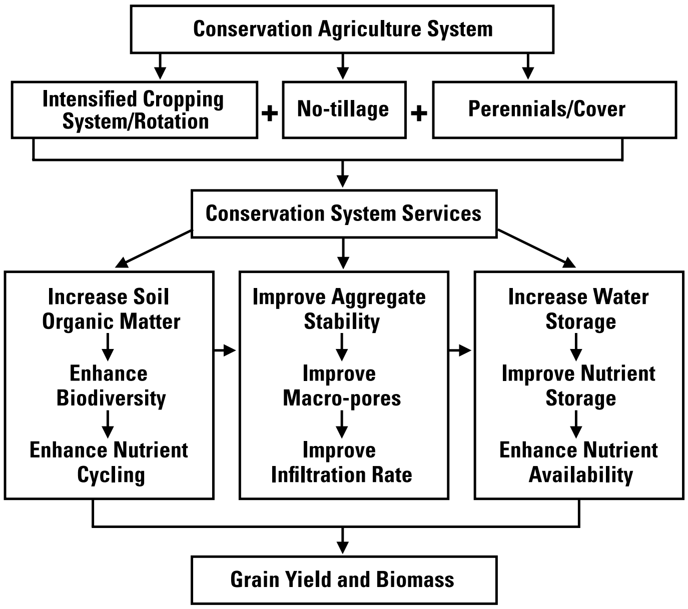


FIGURE 24. System approach for building soil health and productivity (Al-Kaisi, 2015)

The Importance of Soil Health

A healthy soil environment is the foundation for food and fiber production, environmental services, and wildlife habitat. Human activities including some farming practices disrupt vital soil processes such as the building and storage of soil organic carbon, building stable soil aggregates, and nutrient cycling.

The soil has long been perceived as the "home" for the greatest microbial diversity among all ecosystems. Therefore, the ability of soils to remain healthy to prevent degradation is dependent on maintaining the soil biodiversity community that is essential for supporting processes, such as residue decomposition and nutrient cycling, regulation of microclimate, local hydrological processes, suppression of undesirable organisms, and the detoxification of undesirable chemicals in the soil.

Implementation of conservation systems can lead to the improvement of many soil health indicators that are interdependent to provide a balanced soil environment for plant and soil organisms as shown in Figure 24.

SOIL FUNCTIONS AND SERVICES

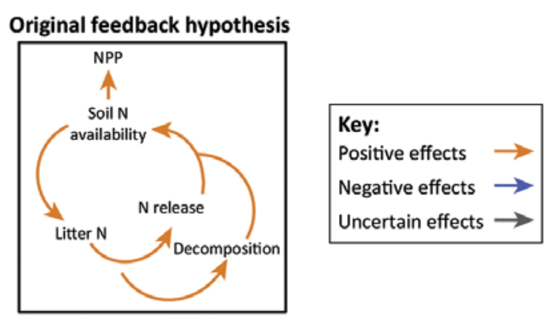
The soil, air, and water are three essential natural resources, and the relationships among them (soil, air, and water) define the unique functions of the soil. The major functions and services of soil are:

- Nutrient cycling
- Water and chemical regulating
- Biodiversity and habitat
- Physical stability and support
- Climate modifier

NUTRIENT CYCLING

Soils are the reservoir of plant nutrients and function by cycling and controlling the release of the nutrients that plants need to produce healthy crops. During nutrient cycling, the following three important plant nutrients, calcium (Ca), nitrogen (N), and phosphorus (P), transform into forms that plants can easily absorb as shown in Figure 25.

Soil microorganisms play a significant role in nutrient cycling. Humified soil organic matter forms a slow/passive pool, whereas the fast/active nutrient pool—such



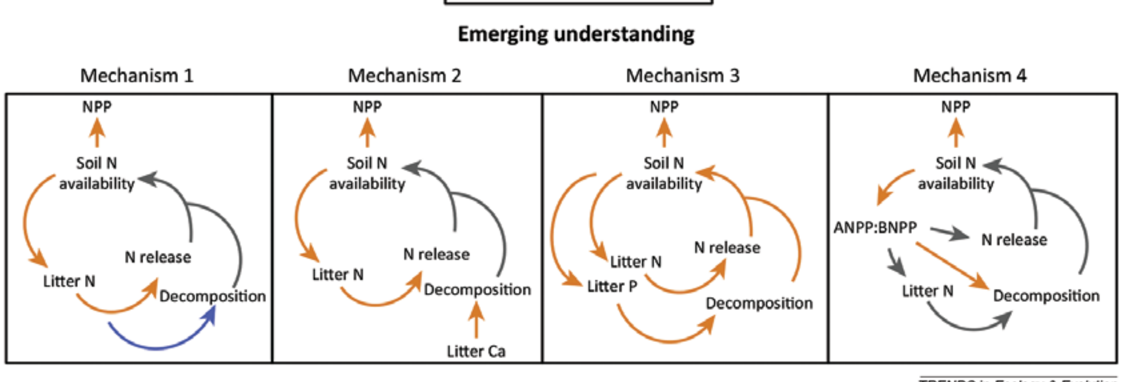


FIGURE 25. Mechanisms of species effect on nutrient cycling. (Source: Hobbie, 2015). NPP= Net Primary Productivity, ANPP= Aboveground Net Primary Productivity, BNPP= Belowground Net Primary Productivity)

as recent plant residues in early stages of decomposition, and soil organisms—has a turnover time of months to years that has the greatest impact on plant growth. In agricultural soils, the interaction between soil microorganisms and nutrient cycling depends on the type of cropping system and crop residue management. When plant residue is left on the soil surface, fungi develop and the population of organisms that feed on fungi increases in the surface layers of the soil. The decomposition of crop residue in the field by soil microorganisms is influenced by the C:N ratio of the crop residue, soil moisture, and soil temperature among other factors.

WATER AND CHEMICALS REGULATION

Soil is a porous medium like any spongy material with the ability to absorb and hold water and dissolved plant nutrients. Therefore, the soil controls and regulates the movement and amount of water and the major plant nutrients through the soil profile. Soil also buffers excess plant nutrients and modifies and filters toxic compounds like arsenic, pesticides, and other chemicals to make them unavailable to plants and animals. Examples of soil ecosystems that regulate and filter chemicals are wetlands (Figure 26). Wetlands function as filters by improving water quality, reducing floods and storm damage, and providing important habitat for fish and wildlife.

FIGURE 26. Restoring Iowa Wetlands (Source: USDA-NRCS. www.nrcs.usda.gov/wps/portal/nrcs/detail/ia/newsroom/factsheets/?cid)

BIODIVERSITY AND HABITAT

Soil provides a diverse physical, chemical, and biological environment that supports the growth of a variety of plants, animals, and microorganisms including bacteria and fungi. Soil diversity, also known as **soil biodiversity**, is the variation in soil life. The soil is also home for a number of organisms such as worms and insects like centipedes. One gram of soil contains a significant number of bacterial cells of different species and other microorganisms.

Neal Smith National Wildlife Refuge, Prairie City, Iowa

Soil microorganisms are responsible for breaking down resistant organic matter (e.g., lignin) or toxic chemicals such as pesticides. The presence of soil biodiversity makes the soil a living ecosystem, and the understanding of the soil as a living ecosystem is the basis for good soil management practices to maintain and enhance soil health.

PHYSICAL STABILITY AND SUPPORT

Healthy soils have the ability to maintain their porous medium to allow the passage of air and water and also withstand the erosive forces of water and air because of the presence of stable aggregates. The soil provides the growing medium and holding support for plant roots and man-made structures like buildings and roads. Healthy soil provides a strong soil structure that can minimize soil compaction under relatively dry soil conditions, especially under natural or conservation agriculture systems as compared to conventional tillage systems.

CLIMATE MODIFIER

Soil plays a key role in amending and modifying the risks and effects of climate variability. It acts as earth's major carbon sink by sequestering atmospheric carbon dioxide and contributes to the mitigation of greenhouse gas emissions by reducing their levels in the atmosphere. The storage of soil carbon contributes to the health of soil and to improvement of the physical, biological, and chemical properties of soil.

3. Management Practices and Soil Health

Soil is the farmer's most valuable natural resource because it provides the growth medium for crop production. Soil is a vital ecosystem that contains actively growing organisms including plant roots and macro- and microorganisms. Production of food and fiber can be improved and sustained in a healthy soil. Therefore, managing the topsoil is essential to crop production

Factors and Management Practices Affecting Soil Health

A number of factors and management practices affect soil health.

FACTORS THAT AFFECT SOIL HEALTH

- Soil properties, which include soil type, texture, drainage, pH, bulk density, aggregate stability, nd soil organic matter.
- The types of crops grown including crop residue, cover crops, cropping systems, and crop rotation.
- The biology of the soil, which includes soil bacterial, fungi, protozoa, nematodes, earthworms, and mammals. The bacteria and fungi contribute to organic matter decomposition and nutrient cycling.
- The environment, which includes factors such as precipitation, temperature, humidity, wind, season length, and carbon dioxide levels.

MANAGEMENT PRACTICES THAT AFFECT SOIL HEALTH

Agricultural management practices that affect soil health include tillage practices, plant diversity, fertilizer application, cover crops, residue management, manure application and use, and field equipment traffic control.

TILLAGE PRACTICES

Tillage practices are major agricultural management practices used for a variety of reasons including seedbed preparation, incorporation of fertilizers and crop residue, and weed control. The effect of tillage on soil health can be very destructive to soil physical and biological properties, such as the loss of organic matter, structure, and reduction of water infiltration. Intensive tillage, especially under moist soil conditions, can cause excessive soil compaction below the tillage depth creating plow pans (Carter, 1994). The conventional tillage practice also destroys biopores and breaks the continuity in soil pores to create depressions and surface ponding and leads to potential soil erosion that can contribute to nutrient and sediment loss (Oades, 1993).

Soil crusting in tilled field

Soybean planted in no-tillage with corn residue

Water infiltration in Strip-tillage (ST) and Conventional-tillage (CT)

Remnant prairie with mixture of grasses and forbs

PLANT DIVERSITY

Planting diverse crop species contributes to soil aggregation. The planting of crops increases soil macro-aggregate stability (Monroe and Kladivko, 1987). Soil aggregate stability varies among different cropping systems and plant species. Different plant species with differing root density and organic exudates as well as degree of mycorrhizal colonization impact soil aggregation and ultimately soil health and biological diversity (Chan and Heena, 1996; Gijsman and Thomas, 1995).

FERTILIZER APPLICATION

Adequate nutrient availability is essential for high crop productivity and quality. When the soil supply of available nutrients is low, use of fertilizers and manures can provide needed nutrients . However, nutrient applications should be based on soil and plant testing as appropriate, and to avoid more than needed inputs that might adversely affect soil and plant growth (Amézketa 1999).

Mixed cover crop

COVER CROPS

Cover crops protect the soil surface from the impact of rain intensity during the off-season by reducing soil erosion and carbon loss and by improving soil macro-aggregates stability (Roberson et al., 1991). Additionally, cover crops such as grasses, legumes, barley, and wheat add carbon to the soil through root exudation, and the decomposition of their dead leaves and roots and the legume fix nitrogen.

Residue removal

Corn growing in no-tillage (NT)

RESIDUE MANAGEMENT

Crop residue left on the soil surface a) protects the soil by minimizing aggregate breakdown from raindrops, thereby increasing aggregate stability (Chan, 1995) and b) enhances water infiltration to reduce soil erosion. The C:N ratio of crop residue and its decomposition rate to release organic carbon influence the soil structure and other soil biological properties. The soil water content, soil temperature, and nitrogen availability influence the rate of residue decomposition.

MANURE USE/APPLICATION

Organic fertilizers such as manure and compost are good sources for increasing soil carbon (C) and nitrogen (N) contents resulting in the increase of microbial biomass C and N (Amézketa et al., 1996). The application of organic byproducts and manure to the soil increases soil water-stable macro-aggregates and micro-aggregation (Metzger et al., 1987). The improvement of soil organic matter with addition of organic sources (dry or liquid) has many benefits in improving nutrient capacity and physical properties of the soil.

TRAFFIC CONTROL

The repeated use of heavy farm equipment for farm operations (such as tillage, planting, and fertilizer and pesticide application) damages the soil structure resulting in soil compaction over time, which affects soil health. Working the field when wet—such as field capacity or saturated condition—can compact the soil and destroy the soil structure. Therefore, avoiding wet conditions and controlling traffic in the field are essential to reducing soil compaction, improving soil health, and preventing yield reduction. Soil compaction resulting from farm equipment is inevitable, but it can be controlled by using the same path during planting, fertilizer and pesticide applications, and during harvest.

In summary, soil tillage is detrimental to soil health as it increases soil organic matter loss and destroys physical properties and soil organisms. The addition of organic matter—including plant residue, manure, or cover crops—to the soil can build soil organic matter over time and protect the soil from erosion by wind and water. Generally, a no-tillage system has many benefits in addition to reduced soil erosion, including increased soil moisture storage, which is essential for yield, especially during dry conditions.

Soil Health and Productivity

Soil is a dynamic ecosystem that supports a diversity of life and provides ecological services and over 90 percent of the food we eat. Management decisions farmers make have profound impact on the overall quality, health, and productivity of the soil. Farmers can keep the soil healthy and productive by doing the following:

- Maintaining topsoil depth by controlling or minimizing soil erosion, sediment, nutrients, and organic matter loss.
- Improving the soil as a medium for root growth and development through reducing, localizing, or eliminating tillage.

Soil erosion

- Using fertilizers, herbicides, and pesticides appropriately to minimize adverse effects on the environment.
- Maintaining live plant growth throughout the growing season by using crop rotations and cover crops.
- Enhancing and maintaining soil biodiversity with conservation practices and agriculture systems that include cover crops, surface residue, strip-tillage, and no-tillage.
- Minimizing and controlling soil compaction.
- Building and maintaining soil organic matter with conservation systems.
- Enhancing water infiltration and retention in the root zone for extraction by plants.
- Minimizing water evaporative losses with soil surface residue using conservation systems (e.g., strip tillage or no-tillage).

Because soil is a dynamic system with multiple functions essential to life, it is appropriate to think about soils in terms of health, vitality, and productivity. From the standpoint of soil productivity, there is strong dependence of grains and biomass production on soil health.

Soil Health Indicators

Depending on land use and location, soil health indicators may differ. However, for agricultural purposes, soil health indicators have been broadly grouped as physical, chemical, and biological (Figure 17). Of the three broad categories of soil health properties, the physical and chemical properties have been well studied by soil scientists and their basic tests and procedures well established. On the other hand, many of the tests for the biological properties of the soil are fairly new and more challenging, given the complexity of the soil biological system. Although soil has inherent qualities (e.g., soil texture) in relation to their physical, chemical, and biological properties within the limits set by a climate ecosystem, soil health changes over time as the result of natural events or human activities. Land managers are the ultimate determinant of its quality or health.

The three major criteria for assessing soil health—the physical, chemical, and biological properties listed in Table 5—are all sensitive to the management practices in Table 4 and climatic changes that affect soil health.

TABLE 4. Agricultural management practices that affect soil health

Activities that degrade soil health	Activities that promote soil health in agriculture land
Aggressive soil tillage	No-tillage or conservation tillage
Annual or seasonal soil fallow	Use of cover crops and relay cropping
Mono-cropping	Diverse crop rotations
Planting of annual crops	Planting of perennial crops
Excessive use of inorganic fertilizers	Organic fertilizer (manures)
Excessive removal of crop residue	Retention of crop residue
Use of broad spectrum fumigants/pesticides	Integrated pest management
Use of broad spectrum herbicides	Weed control by mulching and non-chemical and less soil disturbance methods

Source: Soil biology for resilient, healthy soils (Lehman et al., 2015)

TABLE 5. Selected soil health physical, chemical, and biological indicators that can be assessed in laboratory and field

Soil properties	Soil health indicator	Relationship to soil condition and function	Methods of evaluation and reference
Physical	Bulk density, typically expressed in g/cm^3	Structural support for plants, water, and solute movement, soil aeration	Cylindrical core method, USDA-NRCS, 2008 Arshad et al. 1996.
	Penetration resistance	Soil compaction	Penetration resistance method, Licht and Al-Kaisi, 2005
	Infiltration rate	Soil's ability to allow water movement into and through soil profile	Penetration resistance method
	Water holding capacity	Amount of water held in soil. Provides water for plant and soil organism functions	Single or double ring infiltrometer method, USDA-NRCS, 2008
	Aggregate stability	Provide soil structure and growth environment	Gravimetric Method, Time Domain Reflectometry (TDR)
Chemical	Cation exchange capacity (CEC)	Soil fertility and plant nutrition	Laboratory analysis, Summer and Miller, 1996
	Organic matter (Organic Carbon, Nitrogen and Phosphorus)	Soil fertility, plant nutrition and aggregate stability	Numerous laboratory methods are available SSSA Book Series: 5
	Electrical conductivity (EC)	Indicates how much nutrient is available to plants and salinity levels. Defines microbial activity in the soil	Electrical conductivity pocket meter, USDA-NRCS, 2008
	pH	Plant nutrition, growth, and crop yields, biological and chemical activity in the soil	Portable pH pocket meter, USDA-NRCS, 2011. Standard lab measurements (KCL or water extractions).
	Heavy metals and plant toxins, examples are Copper, Zinc, Nickel, Cadmium and Lead	Plant nutrition in smaller amounts can be harmful to plants. High levels can be harmful for plants or animals.	Reed and Martens, 1996; Amacher, 1996 Soil digestion Cornell test #2021 EPA Method 3051-6010
Biological	Earthworms	Modify soil structure with pores and new aggregates with binding agents responsible for water stable aggregates	Counting the number of earthworms per unit area of soil, USDA-NRCS, 2009
	Microbial biomass carbon	Amount of carbon fixed in microbial community	Guzman and Al-Kaisi, 2010
	Soil microorganisms (bacteria, fungi, nematodes, viruses)	Nutrient cycling, decomposition, and respiration	Culture media, Rai, 1976
	Soil enzymes activities	Influence organic matter decomposition, and nutrient cycling	Biochemical assays, USDA-NRCS, 2010
	Particulate organic matter	Food and energy for soil microorganisms and small animals, CEC, plant nutrients, buffers pH, suppresses soil borne diseases	Several different laboratory methods, Cambardella and Elliot, 1992 Fronning et al., 2008 USDA-NRCS, 2011

4. Soil Health Evaluation

Soil Health Evaluation Methods

Soil health evaluation involves both field and laboratory procedures.

Laboratory methods involve soil sample preparation and analyses of soil samples that may include chemical analyses, such as total carbon, total nitrogen, phosphorus, potassium, CEC, and soil pH, and for the biological characteristics, such as soil microbial biomass carbon and other biological indicators. Also, laboratory procedures can be used for determining soil aggregate stability and other physical properties. Table 5 summarizes the majority of soil health indicators, their relevance, and methods (field and laboratory) for their evaluation, and references of these methods.

Measuring soil surface moisture

Measuring soil compaction

Field methods involve scouting and observation of the field for physical signs of plant stress and soil biological, physical, and hydrological evaluation. These field observations and soil health assessment indicators can be summarized for future reference. Generally, the field assessment for soil health focuses on selected soil properties that are easy to evaluate such as soil structure, compaction, plant appearance, earthworm counts, water infiltration, and other field indicators that are affected by management practices as summarized on the soil health assessment card (Table 6).

Soil Health Assessment

Soil health can be assessed by using the Iowa Health Assessment Card. See its purpose, interpretation, and directions for use below. The card itself is shown in Table 6 beginning on page 31.

PURPOSE OF THE IOWA SOIL HEALTH ASSESSMENT CARD

The Iowa Soil Health Assessment Card (ISHAC) is a tool designed to help farmers, operators, and other agricultural professionals (including Extension educators) evaluate the health of the soil using soil biological and physical indicators in the field. The ISHAC is designed to reflect how well the soil is functioning when compared to its natural or inherent potential and to monitor improvement in soil health based on a person's field experience and working knowledge of a field specific soil resource. Regular use of the ISHAC allows users to monitor long-term trends and changes in soil health due to the effects of soil and crop management activities. The ISHAC provides a qualitative assessment of soil function and evaluation ratings, but does not represent an absolute measure or value and is most effective when filled out consistently by the same person over time. The purpose of using the ISHAC to evaluate soil health is to help users improve their understanding of how management decisions influence soil health and function at a specific farm.

INTERPRETATION OF THE IOWA SOIL HEALTH ASSESSMENT RESULTS

The rating descriptions for each indicator presented on the score card represent the worst and best soil conditions at the time of evaluation. As the ISHAC is used over time, the impact of different management systems can be documented. It is important that individual scorecards for each location are kept as a record to monitor how specific soils are responding to overall soil and crop management decisions. Individuals may also consider using the NRCS Soil Quality Kit to assess the health of specific fields or soils more quantitatively. Contact a USDA-NRCS district conservationist for information on Soil Quality Kit purchase and assistance.

DIRECTIONS FOR USING THE IOWA SOIL HEALTH ASSESSMENT CARD

1. Divide the farm and fields into separate sections for evaluation in the same way operators would divide them for soil fertility sampling: systematic or grid locations, topography, history of tillage, crop rotation, and manure application.
2. Enter the Location, Date, Soil Type, Soil Condition, Crop Type, and Variety Hybrid information for the assessed field at the top of the ISHAC.
3. Use a shovel to get a representative soil sample from more than one spot within each portion of the field.
4. Rate each indicator on a scale from 1 to 10, with 10 being the best. Refer to the Rating Description as a guide to determine the score for each indicator. Record site-specific observations in the Notes section.
5. Review and evaluate the scoring. Follow changes in the soil health indicators over time, examine current field management practices, explore options, and consider alternatives of management changes in problem areas.
6. Consult recommended management practices for improving soil health that are listed in Table 6 (pages 31-32).

TABLE 6. The Iowa Soil Health Assessment Card

Suggested timing for assessment of soil health indicators					
	GROWING SEASON				
	Early Spring	Spring	Summer	Fall	After Rainfall
Structure (aggregate stability, friability)	✓	✓	✓	✓	
Crusting		✓			✓
Compaction	✓	✓	✓	✓	✓
Earthworm	✓	✓			✓
Smell	✓	✓			✓
Residue Decomposition	✓	✓			
Infiltration					✓
Water Holding Capacity	✓	✓	✓	✓	✓
Emergence		✓			
Plant Health		✓	✓	✓	
Root Growth		✓	✓	✓	

Terraces breaking slope

TABLE 6. (Continued) Iowa Soil Health Assessment Card

Date ____________________

Location ____________________ **Crop Type** ____________________ **Variety/Hybrid** ____________________

Soil Type ____________________ **Slope** ____________________ **Corn Suitability Rating** ____________________

Soil Condition ❑ Dry ❑ Moist ❑ Wet

Field Characteristics - Field characteristics do not change frequently and can be checked less frequently

Description – check one per category				**Notes**
Topography	❑ Rolling to hilly	❑ Gently rolling	❑ Flat	____________________
Color	❑ Light	❑ Moderate	❑ Dark	____________________
Soil Texture	❑ Clay	❑ Loam	❑ Sand	____________________
Drainage	❑ Poorly drained	❑ Moderately drained	❑ Well drained	____________________

This Table is adopted from PM2027, Al-Kaisi, 2006

TABLE 6. (Continued) Soil Health Field Indicators

Indicators change with different management practices and therefore need to be determined more frequently.

1. Give a score for each indicator with 10 being best and 1 being poor.
2. For methods to evaluate the soil health indicators below, please consult Table 5.
3. After you complete scoring different indicators, average each major indicator (structure, soil life, soil air and water, and plant life).
4. Use these overall scores for each indicator to determine any correction in management practices recommendations below.

Indicator		Poor	Fair	Good	Observations	Rating Description		
		1-3	4-7	8-10		1-3	4-7	8-10
Soil Tilth	Structure/ aggregation					Hard, lots of clods, difficult to till	Crumbles with pressure, few clods	Crumbles easily, mellow, easy to till
	Crusting					Surface seals easily after tillage and rain	Some sealing with little effect on emergence	Open, porous soil structure throughout growing season
	Compaction/ bulk density					Severely restricted penetration, horizontal root growth	Somewhat restricted penetration, both horizontal and vertical roots	Unrestricted penetration, vertical root growth
Overall Score								
Soil Life	Earthworm					No visible signs of casts or earthworms	Few casts, some earthworms	Many casts, lots of earthworms
	Smell					No or stagnant smell	Some smell to little smell	Pungent, fresh, sweet "earthy" smell
	Residue Decomposition					Residue removed or slow decomposition	Some residue remains, minimal decomposition	Residue left intact and at various stages of decomposition
Overall Score								
Soil Air and Water	Infiltration					Water ponds on the soil surface	Some ponding visible	No ponding
	Water Holding Capacity					Soil has limited capacity, frequent crop stress	Soil has moderate capacity, some crop stress intermittently	Soil holds water well, deep in the top soil, little crop stress
Overall Score								
Plant Life	Emergence					Slow uneven emergence	Inconsistent emergence	Rapid even emergence
	Plant Health					Yellow, stunted growth, variable stand height and population	Variation in color, height, population	Dark green vibrant growth, even stand
	Root Growth					Restricted roots, few fine roots	Somewhat restricted roots, some fine roots	Healthy uninhibited roots, lots of fine roots
Overall Score								

Overall Observation ____

____

TABLE 6. (Continued) Overall Soil Score and Management Practice Recommendations

Soil Health Indicator	Score	Management Practice Recommendation
Overall Soil Tilth	1-3	Use conservation practices such as no-tillage, strip-tillage, crop rotation with cover crops, apply manure, compost, reduce traffic and don't work wet soils.
	4-7	Use cover crops and animal and plant-based soil amendments such as compost/farm yard manure.
	8-10	Maintain current soil management practices.
Overall Soil Life	1-3	Avoid/minimize soil tillage, leave crop residue after harvest, cover crop, crop rotation, and apply manure and compost.
	4-7	Apply manure and compost, leave crop residue on soil surface, include cover crop.
	8-10	Avoid soil tillage; maintain current soil management practices.
Soil Air and Water	1-3	Avoid bare soil surfaces, leave crop residue on the soil surface, consider tile drainage if condition is persistent annually, add cover crop, and eliminate tillage.
	4-7	Control traffic to avoid soil compaction, consider switching to no-tillage, strip-tillage, and use cover crop.
	8-10	Maintain current soil management practice.
Plant Life	1-3	Replant if plant population is extremely low and condition allows. Apply lime. N, P, K and other crop nutrients as needed for optimal production, herbicides and pesticides for weed and disease control.
	4-7	Apply lime, N, P, K and other crop nutrients as needed for optimal crop production.
	8-10	Maintain current management practices with special attention to proper fertilizer and manure application rates.

References

Al-Kaisi, M. 2015. Building soil health for sustainable agriculture systems, pp.157-164 *in* Proc. 27th Annual Integrated Crop Management Conference, Iowa State University, Ames, Iowa. Dec. 2-3.

Al-Kaisi, M. 2002. How to evaluate soil moisture in the field. Iowa State University Extension Integrated Crop Management Newsletter IC-484(6), April 24, 2000.

Al-Kaisi, M., A. Doulle, and D. Kwaw-Mensah. 2014. Soil microaggregate and macroaggregate decay over time and soil carbon changes as influenced by different tillage systems. *JSoilWaterCons* 69(6): 574-580.

Al-Kaisi, M. M., X. Yin, and M. A. Licht. 2005. Soil carbon and nitrogen changes as affected by tillage systems and crop biomass in a corn-soybean rotation. *Applied Soil Ecology* 30:174-191.

Altieri, M. A. 1999. The ecological role of biodiversity in agroecosystems. *Agriculture, Ecosystems and Environment* 74:19-31.

Amacher, M. C. 1996. Nickel, Cadmium and Lead, Chapter 28 *in* Methods of Soil Analysis Part 3-Chemical Analysis. SSSA Book Series: 5. Madison, Wis.

Amézketa, E. 1999. Soil aggregate stability: A review. *JSustainAg* 14 (2/3):83-151.

Amézketa, E., M. J. Singer, N. Gunapala, K. Scow, D. Friedman, and E. Lundquist. 1996. Testing a procedure measuring water-stable-aggregation. *SSSAJ* 60:888-894.

Anderson, S. H., C. J. Gantzer, J. M. Boone, and R. J. Tully. 1988. Rapid nondestructive bulk density and oil-water content determination by computed tomography. *SSSAJ* 52:35-40.

Angers, D. A. and Carter, M. R. 1996. Aggregation and organic matter storage in cool, humid agricultural soils, pp. 193–211 *in* M. R. Carter and B. A. Stewart, Structure and organic matter storage in agricultural soils. CRC Press, Boca Raton, Fla.

Arshad, M.A., B. Lowery, B. Grossman. 1996. Physical tests for monitoring soil quality, pp. 123-141 *in* Doran, J.W., Jones, A.J. (Eds.), Methods for Assessing Soil Quality. SSSA Special Publication No. 49. Madison, Wis.

Astera, M. 2014. Cation exchange capacity in soils, simplified, *in* Chapter 2, The Ideal Soil: A Handbook for the New Agriculture. SoilMinerals.com. http://soilminerals.com/Cation_Exchange_Simplified.htm.

Ball, J. 2015. Soil and water relationships. The Samuel Roberts Noble Foundation, Inc. http://www.noble.org/ag/Soils/SoilWaterRelationships/.

Bauer, A., and A. L. Black. 1981. Soil carbon, nitrogen, and bulk density comparisons in two cropland tillage systems after 25 years and in virgin grassland. *SSSAJ* 45 (6): 1166-1170.

Bot, A., and J. Benites. 2005. The importance of soil organic matter: Key to drought resistance soil and sustained food production. Food and Agriculture Organization of the United Nation Soils Bulletin 80. Rome, Italy.

Bouwere, H. 1986. Intake rate: cylinder infiltrometer. pp.825-844, in Klute A. (ed.), Methods of Soil Analysis. Part 1. ASA and SSSA, Madison, Wis.

Boyd, J. and S. Banzhal. 2007. What are ecosystem services: The need for standardized accounting units. *Ecological Economics* 63:616-626.

References

Brady, N.C., and R. Weil. 1999. The nature and properties of soils. 12th ed. Prentice Hall, Upper Saddle River, N.J.

Brevik, E. C. 2009. Soil Health and Productivity. In Soils, Plant Growth and Crop Production. W. Verhye (Ed.). Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO, EOLSS Publishers, Oxford, UK. http://www.eolss.net (accessed on 13 July, 2015).

Bronick, C. J. and R. Lal. 2005. Soil structure and management: a review. *Geoderma* 124:3-22.

Cambardella, C.A., and E. T. Elliot. 1992. Particulate soil organic matter changes across a grassland cultivation sequence. *SSSAJ* 56:777-783.

Carter, M. 1994. A review of conventional tillage strategies for humid temperate regions. *SoilTillRes* 23:361-372.

Cavalieri, K. M. V., A. P. da Silva, C. A. Tormena, T. P. Leão, A. R. Dexter, and I. Håkansson. 2009. Long-term effects of no-tillage on dynamic soil physical properties in a Rhodic Ferrasol in Paraná, Brazil. *SoilTillRes* 103:158-164.

Chan, K. Y. 1995. Enhanced structural stability of a straw amended soil in the presence of gypsum. *CommSoilSciPlantAnal* 26:1023-1032.

Chan, K. Y. and D. P. Heenan. 1996. The influence of crop rotation on soil structure and soil physical properties under conventional tillage. *SoilTillRes* 37:113-125.

Cline, M.G. 1961. The changing model of soil. SSSA Proceedings 25:442–446.

Cook, B., R. Miller, R. Seager. 2011. Did dust storms make dust bowl drought worse? Drought Research. Lamont-Doherty Earth Observatory. The Earth Institute at Columbia University. New York, N.Y. http://ocp.ldeo.columbia.edu/res/div/ocp/drought/dust_storms.shtml (accessed January 5, 2016).

Cornel Soil Health. 2015. Cornell Soil Health Testing. Department of Horticulture, College of Agriculture and Life Sciences, Cornell University, Ithaca, N.Y.

da Silva, A. P., B. D. Kay, and E. Perfect. 1997. Management versus inherent properties effects on bulk density and relative compaction. *SoilTillRes* 44:81-93.

de Groot, R.S., M. A. Wilson, and R. M. J. Boumans. 2002. A typology for the classification, description and valuation of ecosystem functions, goods and service. *Ecological Economics* 41 (3): 393-408.

Dias, T., A. Dukes and P. M. Antunes. 2015. Accounting for soil biotic effects on soil health and crop productivity in the design of crop rotations. *JSciFoodAgr* 95:447-454.

Dorn, J. W. and T. B. Parkin. 1996. Quantitative indicators of soil quality: a minimum data set, *in* J.W. Doran and A. J. Jones (eds). Methods for assessing soil quality. SSSA Inc., Madison, Wis.

Doran, J. W., M. Sarrantonio and M. Liebig. 1996. Soil health and sustainability. *AdvAgron* 56:1-54.

Emerson, E. 2015. How to use the soil texture triangle. www.had2know.com/garden/classify-soil-texture-triangle-chart.html.

Engelmann, M. D. 1961. The role of soil arthropods in the energetics of an old field community. Ecological monographs 31 (3):221-238. http//www.jstor.org/stable/1948553 (accessed December 15, 2015).

Enwezor, W. O. 1976. The mineralization of nitrogen and phosphorus in organic material of varying C:N and C:P ratios. *Plant&Soil* 44:237-240.

References

Eswaran, H., R. Lal, and P.F. Reich. 2001. Land degradation: An overview *in* Bridges, E.M., I. D. Hanna, L. R. Oldeman, F.W.T. Pening de Vries, S. J. Scherr, and S. Sompatpanit (eds.). Responses to Land Degradation. Proc. 2nd International Conference on Land Degradation and Desertification. Khon Kaen, Thailand. Oxford Press, New Delhi, India.

Evertson, J. 2013. Living soils sustain landscape. Beneficial landscapes, the plants, wild life, soil, and water of our gardens. http://beneficiallandscapes.blogspot.com/2013/02/living-soils-sustain-landscapes.html (accessed December 17, 2015).

Fronning, B. E., K. D. Thelen, and D. Min. 2008. Use of manure, compost, and cover crops to supplant crop residue carbon in corn stover removed cropping systems. *AgronJ* 100:1703-10.

Gans, J., M. Wolinsky and J. Dunbar. 2005. Computational improvements reveal great bacterial diversity and high metal toxicity in soil. *Science* 309:1387-1390.

Gijsman, A. J. and R. J. Thomas. 1995. Aggregate size distribution and stability of an oxisol under legume-based and pure grass pasture in the eastern Colombian savannas. *AustJSoilRes* 33:153-165.

Global Issues. Source: http://agriculturesociety.com/politics-and-food/the-importance-of-soil-diversity-to-health-and-the-environment/.

Gupta, V. 2014. Microbes and soil structure. Encyclopedia of Earth Sciences Series pp 470-472.

Guérif, J., G. Richard, C. Dürr, J. M. Machet, S. Recous, and J. Roger-Estrade. 2001. A review of tillage on crop residue management, seedbed conditions and seedling establishment. *SoilTillRes* 61:13-32.

Guzman, J., and M. Al-Kaisi. 2010. Soil Carbon Dynamics and Soil Carbon Budget of Newly Reconstructed Tall-grass Prairies in South Central Iowa. *JEnvironQuality* 39:136-146.

Guzman, J. and M. M. Al-Kaisi. 2011. Landscape position effect on selected soil physical properties of reconstructed prairies in south central Iowa. *JSoilWaterCons* 66:183-191.

Hillel, D. 1998. Environmental soil physics. Academic Press. San Diego, Calif.

Hobbie, S. E. 2015. Plant species effects on nutrient cycling: revisiting litter feedbacks. *TrendsEcologyEvolution* 30 (6):357-363.

Hoorman, J. J. 2011. The role of soil bacteria. Fact Sheet. Agriculture and Natural Resources SAG13-11. The Ohio State University Extension, Columbus, Ohio.

Huisman, J., A. C. Speril, W. Bouten, J. M. Vestraten. 2001. Soil water content measurements at different scales: accuracy of time domain reflectometry and ground-penetrating radar. JHydrology 245:48-58.

Ingram, E. R., A. R. Moldenke, C. A. Edwards. 2002. Soil Biology Primer, (eds. 2000 A. J. Tugel, A. M. Lewandoski, and D. Happe-vonArb). Ankeny, Iowa: Soil and Water Conservation Society. Online primer: Soil Biology Primer available at http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/biology/.

References

Jastrow, J. D., T. W. Boutton and R. M. Miller. 1996. Carbon dynamics of aggregate-associated organic matter estimated by carbon13 natural abundance. *SoilSciSocAmJ* 60:801-807.

Jauron, R. 2002. The meaning and importance of soil pH. Iowa State University Extension and Outreach publication IC-487 (12), Ames, Iowa. May 24, 2004. http://www.ipm.iastate.edu/ipm/hortnews/2002/5-24-2002/soilph.html (accessed November 13, 2015).

Jeffries, P., S. Gianinazzi, S. Perotto, K. Turnau, and J. M. Barea. 2003. The contribution of arbuscular mycorrhizal fungi in sustainable maintenance of plant health and soil fertility. *BiolFertSoils* 37:1-16.

Joint Research Centre. 2015. Soil Biodiversity. Atlas of soil biodiversity. http://esdac.jrc.ec.europa.eu/themes/soil-biodiversity.

Jones, M. J. and J. W. Parsons. 1970. The influence of soil C/N rations on nitrogen mineralization during anaerobic incubation. *PlantSoil* 32:258-262.

Kaye., J, and S. C. Hart. 1997. Competition for nitrogen between plants and soil microorganisms. *TrendsEcolEvol* 12:139–143.

Karlen, D., M. Mausbach, J. Doran, R. Cline, R. Harris, and G. Schuman. 1997. Soil quality: A concept, definition and framework for evaluation (a guest editorial). *SSSAJ* 61(1):4-10.

Kutílek, M. 2004. Soil hydraulic properties as related to soil structure. *SoilTillRes* 79:175-184.

Lehman, R. M., V. Acosta-Martinez, J. S. Buyer, C. A. Cambardella, H. P. Collins, T. F. Ducey, J. J. Halvorson, V. L. Jin, J. M. F. Johnson, R. J. Kremer, J. G. Lundgren, D. K. Manter, J. E. Maul, J. L. Smith, and E. Stott. 2015. Soil biology for resilient, healthy soil. *JSoilWaterCons* 70(1):12A-18A.

Lewis, B. G. Soil chemistry. Environmental and Ecological Chemistry Vol II. Encyclopedia of life support ystem (EOLSS). Soil Chemistry, Northwestern University, Evanston, Ill. archived from www.eolss.net/Sample-Chapters/C06/E6-13-13-00.pdf (accessed December 09, 2015).

Licht, M. A. and M. Al-Kaisi. 2005. Strip-tillage effect on seedbed soil temperature and other soil physical properties. *SoilTillRes* 80:233-249.

Lin, H. S., K. J. McInnes, L.P. Wilding, and C. T. Hallmark. 1996. Effective porosity and flow rate with infiltration at low tensions in a well-structured subsoil. *Trans ASAE* 39:131-133.

Lin, H. S., K. J. McInnes, L.P. Wilding, and C. T. Hallmark. 1999. Effects of soil morphology on hydraulic properties. I. Quantification of soil morphology. *SSSAJ* 63:948-954.

Lipiec, J., J. Kuś, A. Słowińska-Jurkiewicz and A. Nosalewicz. 2006. Soil porosity and water infiltration as influenced by tillage methods. *SoilTillRes* 89:210-220.

Mallarino, A. P. and J. Sawyer. 2011. Corn and soybean response to soil pH and liming. Integrated Crop Management Conference 1993. Iowa State University. Ames, Iowa.

Mallarino, A. P. and J. Sawyer. 2013. Update to Iowa phosphorus, potassium and lime recommendations. Integrated Crop management News, Iowa state University Extension and Outreach, Ames, Iowa. https://crops.extension.iastate.edu/cropnews/2013/09/update-iowa-phosphorus-potassium-and-lime recommendations (accessed November 13, 2015).

References

Mallarino, A. P., J. Sawyer, and S. Barnhart. 2013. A general guide for crop nutrient and limestone recommendations in Iowa. PM 1688 Revised October 2013. Iowa State University Extension and Outreach, Ames, Iowa. https://store.extension.iastate.edu/Product/A-General-Guide-for-Crop-Nutrient-and-Limestone-Recommendations-in-Iowa (accessed November 13, 2015).

McBrantney, A., D. J. Field, and A. Koch. 2014. The dimensions of soil security. Geoderma 213:203-213.

McElrone, A. J., B. Choat, G. A. Gambetta, and C. R. Brodersen. 2013. Water Uptake and Transport in Vascular Plants. *NatureEducationKnowledge* 4(5):6.

McKenzie, N., D. Jacquier, R. Isbell, and K. Brown. 2004. Australian soils and landscapes: An illustrated compendium. CSIRO Publishing: Collingwood, Victoria.

Metzger, L., D. Levanon, and U. Mingelgrin.1987. The effect of sewage sludge on soil structural stability: Microbiological aspects. *SoilSciSocAmJ* 51:346-351.

Miller, R. M. and J. D. Jastrow. 2002. Mycorrhizal fungi influence soil structure *in* Kapulink, Y and D. D. Douds Jr. (eds.), Arbuscular mycorrhizae: Physiology and Function, 3-18. Academic Publishers. The Netherlands.

Moldenke, A.R. The living soil: Arthropods. USDA-NRCS. http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/health/biology/?cid=nrcs142p2_053861 (accessed November 13, 2015).

Monroe, C. D. and Kladivko, 1987. Aggregate stability of a silt loam soil as affected by roots of corn, soybeans and wheat. *CommunSoilSciPlantAnal* 18:1077-1087.

Nichols, K. Gomalin: Hiding place for a third world's stored soil carbon. www.ars.usda.gov/is/AR/archive/sep02/soil0902.htm (accessed November 13, 2015).

Nichols, K. Does glomalin hold your farm together? http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1144429.pdf.

Nichols, K. 2008. Gomalin is key to locking up soil carbon. ScienceDaily. 2 July 2008. https://www.sciencedaily.com/releases/2008/06/080629075404.htm (accessed October 21, 2015).

Oades, J. M. 1993. The role of biology in the formation, stabilization and degradation of soil structure.*Geoderma* 56:377-400.

O'Geen, A. T. 2012. Soil Water Dynamics. *NatureEducationKnowledge* 3(6):12.

Osman, K. T. 2013. Chemical properties of soil. Chapter 8, in Soils: Principles, Properties and Management. Springer, New York.

Panayiotopoulos, K. P. C. P. Papadopoulos, and A. Hatjiioannidou. 1994. Compaction and enetration resistance of an Alfisol and Entisol and their influence on root growth of maize seedlings. *SoilTillRes* 31: 323-337.

Parr, J. F., R.I. Papendick, S.B. Hornick and R.E. Meyer. 1992. Soil quality: Attributes and relationship to alternative and sustainable agriculture. *AmJAltAg* 7:5-11. doi:10.1017/S0889189300004367.

References

Petrovic A.H., J. E. Siebert, and P. E. Lieke. 1982. Soil bulk density analyses in three dimension by computed tomographic scanning. *SSSAJ* 46: 445–450.

Pidwirny, M. 2013. Soil. https://editors.eol.org/eoearth/wiki/Soil (accessed December 17, 2015).

Pidwirny, M. 2006. Introduction to soils. Fundamentals of Physical Geography, 2nd Edition. http://www.physicalgeography.net/fundamentals/10t.html (accessed December 17, 2015).

Rai, B. 1976. Study of fungi on decaying leaves of *saccharum munja* by differential washing techniques. *PlantSoil* 44:233-236.

Rawls, W. J. 1983. Estimating soil bulk density from particle size analysis and organic matter content. *SoilSci* 136: 48–55.

Reed, S. T. and D. C. Martens. 1996. Copper and Zinc. Chapter 26 in Methods of Soil Analysis Part 3-Chemical Analysis. SSSA Book Series: 5. Madison, Wis.

Reicosky, D. C., W. D. Kemper, G W. Langdale, C. L. Douglas Jr., and P. E. Rasmussen. 1995. Soil organic matter changes resulting from tillage and biomass production. *JSoilWaterConserv* 503:253-261.

Richter, D. deB, and D. H. Yaalon. 2012. The changing model of soil. Revisited. *SSSAJ* 76:766-778.

Ritchey, E., J. McGrath and D. Gehring. 2015. Determining soil texture by feel. Cooperative Extension Service, GR-217. University of Kentucky College of Agriculture, Food and Environment. Lexington, Ky.

Robertson, E. B. 1991. Extracellular polysaccharide production by soil bacteria: Environmental control and significance in agricultural soils. PhD dissertation. University of California, Berkeley.

Rossi, A. M., D. R. Hirmas, R. C. Graham, and P. D. Sternberg. 2008. Bulk density determination by automated three-dimensional laser scanning. *SSSAJ* 72: 1591-1593.

Russell E. J. and A. Appleyard. 1915. The atmosphere of the soil: its composition and the causes of variation. *JAgSci* 7:1-48. DOI: 10.1017/S0021859600002410.

Schloss, P. D. and J. Handelsman. 2006. Toward a census of bacteria in soil. *PLos Computation Biology* 2(c92), doi:10.137/journal/pcbi.0020092.

Schmugge, T. J., T. J. Jackson, and H. L. Mckim. 1980. Survey of methods for soil moisture determination. *WaterResourcesRes* 16 (6): 961-979.

Singh, B. and J. Ryan. 2015. Managing fertilizer to enhance soil health. First Edition. IFA, Paris, France.

Six, J., E. T. Elliot, K. Paustian and J. W. Doran. 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. *SSSAJ* 62:1367-1377.

Six, J., E. T. Elliott, and K. Paustian. 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. *SoilBiolBiochem* 32, 2099-2103.

Smith, S. E., and F. A. Smith. 2011. Roles of arbuscular mycorrhizas in plant nutrition and growth: New paradigms from cellular to ecosystem scales. *AnnRevPlantBio* 62:227-250.

Smith, J. L. and J. W. Doran. 1996. Measurement and use of pH and electrical conductivity for soil quality alysis *in* Methods for assessing soil quality. SSSA Special Publication 49: 169-182.

Soil Secrets. 2012. Understanding the importance of cation exchange capacity. Soil Secrets LLC. http://www.soilsecretsblog.com/2012/01/understanding-importance-of-cation.html.

References

Subbarao, G. V., K. L. Sahrawat, K. Nakahara, T. Ishikawa, M. Kishii, I. M. Rao, C. T Hash, T. S. George, P. Srinivasa Rao, M. Nardi, D. Bonnett, W. Berry, K. Suenaga, and J. C. Lata. 2012. Biological nitrification inhibition: A novel strategy to regulate nitrification in agricultural systems. *AdvAgron*, Elsevier, 114:249-302.

Summer, M. E. and W. P. Miller. 1996. Cation exchange capacity and exchange coefficients. Chapter 40 *in* Methods of Soil Analysis Part 3-Chemical Analysis. SSSA Book Series: 5. Madison Wis.

Tate, K. W., D. M. Dudley, N. K. McDougald, and M. R. George. 2004. Effect of canopy and grazing on soil bulk density. *RangelandEcologyMgt* 57 (4): 441-417.

Tébrügge, F., and R. A. Dürring. 1999. Reduced tillage intensity-a review of results from a long-term study in Germany. *Soil & Till Res*. 53:15-28.

Thien, S. J. 1979. A flow diagram for teaching texture by feel analysis. *JAgronEdu* 8:54-55.

Timm, L. C., L. F. Pires, K. Reichardt, R. Roveratti, J. C. M. Oliveira, and O. O. Bacchi. 2005. Soil bulk density evaluation by conventional and nuclear methods. *SoilRes* 43 (1): 97-103.

Topp, G. C., J. L. Davis, and A.P.Anna. 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *WaterResourcesRes* 16 (3): 574-582.

Tracy, B. F. and Y. Zhang. 2008. Soil compaction, corn yield response, and soil nutrient pool dynamics within an integrated crop-livestock system in Illinois. *CropSci* 48:1211-1218.

Trojan, M. D. and D. R. Linden. 1998. Macroporosity and hydraulic properties of earthworm-affected soils as influenced by tillage and residue management. *SSSAJ* 62:1687-1692.

United Nations. 2013. World population prospects: The 2012 Revision. Department of Economic and Social Affairs, Population Division.

https://esa.un.org/unpd/wpp/publications/Files/WPP2012_HIGHLIGHTS.pdf

USDA. Granular soil USDA-NRCS Soil Survey Manual, Chapter 3, part 7 https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcs142p2_054253#particle_size

USDA-NIFA. 2015. Porosity. Soils–Part 2: Physical properties of soil and soil water. Plant and Soil Sciences eLibrary.

USDA-NRCS. Mineral Composition of the Soil. NRCS Soil Survey Manual, Chapter 3, part 7. http://soils.usda.gov/technical/manual/contents/chapter3g.html (accessed November 13, 2015).

USDA-NRCS. 2014. Soil bulk density/moisture/aeration. Soil Quality Kit–Guides for Educators 2014. nrcs142p2_053260.pdf.

USDA-NRCS. 2011. Soil quality indicators: Soil electrical conductivity. nrcs142p2_053136.pdf.

USDA-NRCS. 2009. Soil quality indicators: Earthworms. nrcs142p2_053137.pdf.

USDA-NRCS. 2011. Soil quality indicators: Particulate organic matter. nrcs142p2_053138.pdf.

USDA-NRCS. 2010. Soil quality indicators: Soil enzymes. nrcs142p2_053139.pdf.

USDA-NRCS. 2008. Soil quality indicators: Available water capacity. nrcs142p2_051590.pdf.

USDA-NRCS. 2008. Soil quality indicators: Bulk density. nrcs142p2_051591.pdf.

USDA-NRCS. 2008. Soil quality indicators: Infiltration. nrcs142p2_051592.pdf.

USDA-NRCS. The Soil Profile. nrcs142p2_054308.

References

USDA-NRCS. Guide to texture by feel. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/edu/?cid=nrcs142p2_054.

USDA-NRCS. Restoring Iowa Wetlands. https://prod.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_006832.pdf

Van der Heijden, M. G. A., R. D. Bardgett, and N. M. van Straalen. 2008. The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystem. *EcologyLetters* 11:296-310.

Van der Heijden, M. G. A., R. Streitwolf-Engel, R. Rield, S. Siegrist, A. Neudecker, K. Ineichen, T. Boller, A. Wiemken and I. R. Sanders. 2006. The mycorrhizal contribution to plant productivity, plant nutrition and soil structure in experimental grassland. *NewPhytologist* 172:739-752.

Van Haveren, B. P., 1883. Soil bulk density as influenced by grazing intensity and soil type on a shortgrass prairie site. *JRangeMgt* 36 (5):586-588.

Wagg C., S. F. Bender, F. Widner, and M. G. A. van der Heijeden. 2014. Soil biodiversity and soil community composition determine ecosystem multifunctionality: Proceedings of the National Academy of Sciences 111 (4): 5266-5270.

Wallace, K. J. 2007. Classification of ecosystem services: Problems and solutions. *BioConservation* 139:235-246.

Wander, M. and J. Gruver. 2008. Soil management practices: Tillage. Soil Quality for Environmental Health. http://www.soilquality.org/management/soil_management_practices.html.

Wander, M.M., S. J. Traina, B. R. Stinner, and S. E. Peters. 1994. Organic and conventional management effects on biologically active soil organic matter pools. *SSSAJ* 58:1130-1139.

Whiting, D., A. Card, C. Wilson, C. Moravec, and J. Reader. 2014. Managing soil tilth: Texture, Structure and Pore Space. Colorado Master Gardener Program. CMG GardenNotes #213. Colorado State University Extension, Fort Collins, Colo.

Whiting, D., A. Card, C. Wilson, C. Moravec, and J. Reader. 2014. Managing soil tilth: Texture, Structure and Pore Space. Colorado Master Gardener Program. CMG GardenNotes #214. Colorado State University Extension, Fort Collins, Colo.

Wilson, K. B., P. J. Hanson, P. J. Mulholland, D. B. Baldocchi, and S. D. Wullschleger. 2001. A comparison of methods for determining forests evapotranspiration and its component: sap-flow, soil water budget, eddy covariance and catchment water balance. *AgriForestMeteorology* 106:153-168.

Wright, S. 2006. A microscopic view of an arbuscular mycorrhizal fungus growing on a corn root. http://www.ars.usda.gov/is/graphics/photos/sep02/k9968-1.htm.

Wright, S. 2002. Arbuscular mycorrhizal fungus growing on corn root. Source: http://www.ars.usda.gov/is/graphics/photos/sep02/k9968-1.htm.

Zou, X. M., H. H. Ruan, Y. Fu, X. D. Yang, and L. Q. Sha. 2005. Estimating soil labile organic carbon and potential turnover rates using a sequential fumigation-incubation procedure. *SoilBiologyBiochem* 37:1923-1928.

Glossary

Actinomycetes. Gram-positive anaerobic bacteria that form branching filaments.

Aggregate stability. Ability of soil particles bound together by cohesive forces to withstand any applied pressure or force, especially from rain.

Algae. Oxygen evolving photosynthetic organisms that contain plant-like chlorophyll (for example, seaweed).

Arbuscular. Intricately branched fungal hyphae (arbuscules) in the cortex of plant roots.

Arbuscular mycorrhizal fungi. A type of mycorrhiza in which the fungi penetrate the cortical cells of the roots of a vascular plant.

Bacteria. Tiny living single cell organisms (microorganisms) that are neither plants nor animals but belong to a group all by themselves either shaped like a ball, a rod, or a spiral.

Capillary action. Upward movement of water at field capacity in the soil micropores.

Capillary water. Water at field capacity held in the soil micropores.

Cations. Positively charged ions in the soil.

Cation exchange capacity (CEC). The number of exchangeable cations per dry weight that a soil is capable of holding, at a given pH value, and available for exchange with the soil water solution.

C/N ratio. Ratio of the mass of carbon (C) to the mass of nitrogen (N) in a plant material.

Cover crops. Crops grown on a piece of agriculturally productive land primarily to manage and control soil erosion, soil fertility, and water quality.

Crop residue. Plant materials including stalks, stems, leaves, and seed pods left in the field after harvest.

Decomposition. Natural processes by which large and complex organic materials are broken down into smaller and simpler ones with the release of carbon dioxide and water as by-products.

Ecosystem. A given area where all living things and the non-living environment interact with each other.

Ecosystem services. Benefits gained by humans from ecosystems.

Fertilizer. Any chemical or organic substance applied to the soil to increase the nutrients in the soil, soil diversity, and soil health.

Field capacity. Soil water condition when excess soil water has stopped draining from a saturated soil after a rain or irrigation event.

Force of gravity. Force that acts on an object from the earth's acceleration called the acceleration of gravity.

Fungi. Small and generally microscopic plants that have no chlorophyll and vascular tissues, and that live on dead organic matter.

Glomalin. Glue-like substance secreted by the hyphae of arbuscular mycorrhizal fungi and that aids in building soil aggregates.

Gravitational potential. Soil water energy by the pull of the force of gravity when the soil is saturated with water.

Habitat. Ecological environment occupied by a group of species.

Humus. Completely decomposed soil organic matter.

Hygroscopic water. Soil water at the permanent wilting point.

Hyphae. Filament-like ramified fungal structures in the soil and in some cases in the root of plants as in the mycorrhiza.

Immobilization. Conversion of inorganic compounds to organic compounds by soil microorganisms or plants.

Ion. An atom that has either lost or gained an electron or electrons.

Leaching. Downward movement of dissolved soil nutrients with soil water beyond the root zone.

Lignin. A complex organic substance with cellulose in plants.

Matric potential. The force of attraction between soil water and the surfaces of soil particles.

Microbial biomass carbon. Carbon of soil bacteria and fungi.

Mineralization. Decomposition of organic matter to release carbon, nitrogen, and other elements into mineral forms.

Mycorrhiza. A symbiotic combination of the mycelium of fungi and plant roots.

Nematode. Round worms of the phylum Nematoda that occur as free-living parasites in the soil.

No-tillage. Soil conservation practice in which seeds are directly drilled into the soil with crop residue at the soil surface without overturning or mixing the soil.

Nutrient cycling. Transformation and movement of soil nutrients in the soil.

Osmotic potential. The force of attraction between soil water and dissolved salts and nutrients.

Permanent wilting point (PWP). Soil water condition when all the micropores are filled with air.

Plant available water (PAW). Soil water held between field capacity and the permanent wilting point that plants can extract and use.

Protozoa. Single-cell free-living microscopic organisms in the soil.

Soil aggregate. A group of primary soil particles that strongly adhere to each other rather than to others surrounding them.

Soil biodiversity. A group of plants, animals, and microorganisms in the soil.

Soil bulk density. Ratio of the dry mass of soil to the bulk volume of the soil (grams/cm^3).

Soil fertility. Capacity of the soil to support plant growth by providing plants with essential plant nutrients.

Glossary

Soil health. Continued capacity of the soil to function within natural or managed ecosystem boundaries to sustain plant and animal productivity.

Soil organic matter. Living plant roots and microorganisms, dead plant and animal tissues at various stages of decomposition, and soil animals.

Soil organic carbon. A component of soil organic matter or other organic sources.

Soil pH. Concentration of free hydrogen ions (H+) in the soil.

Soil productivity. The functioning of soil resulting from the balance in the growth factors of the physical, chemical, and biological properties of the soil.

Soil nutrient pool. The reservoir of nutrients in the soil.

Strip-tillage. A tillage system in which the tilled zone is 20 centimeters wide and 10 centimeters deep in close proximity to previous plant rows.

Tillage. Mechanical breaking, overturning, and mixing of the soil.

Traffic. Movement of vehicles, equipment, humans, and animals on the soil.

Water infiltration. Movement of water into the soil through soil surface and macrospores.

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Table 1	p.4	Brady and Weil, 1999
Table 2	p.6	Al-Kaisi, 2000
Table 3	p.16	USDA-NRCS Soil Quality Kit-Guide for Educators 2014
Table 4	p.27	Lehman et al., 2015
Table 6	p.31	Adopted from PM2027, Al-Kaisi, 2006
Figure 1	p.2	USDA-NRCS
Figure 2	p.3	Pidwirny, 2006
Figure 3	p.3	Justin Everson, 2013
Figure 4	p.4	Whiting et al., 2014
Figure 5	p.4	Ritchey et al., 2015
Figure 6	p.5	USDA-NRCS Guide to Texture by Feel, modified from S. J. Thein, 1979
Figure 7	p.6	University of Minnesota Extension, adapted from NRCS
Figure 8	p.7	Emerson, 2015
Figure 9	p.7	Whiting et al., 2014
Figure 10	p.8	Whiting et al., 2014
Figure 11	p.8	Whiting et al., 2014
Figure 12	p.9	McElrone et al., 2013
Figure 13	p.10	USDA-NRCS
Figure 14	p.11	O'Green, 2012
Figure 15	p.14	Photo by Sara Wright, USDA-ARS
Figure 16	p.14	Kris Nichols, USDA-ARS
Figure 17	p.15	Mahdi Al-Kaisi, 2015
Figure 18	p.16	Mahdi Al-Kaisi, 2015
Figure 19	p.17	Mahdi Al-Kaisi, 2015
Figure 20	p.18	"Soil as a Plant Sees It," University of Nebraska–Lincoln, 1991
Figure 21	p.19	Mahdi Al-Kaisi
Figure 22	p.19	Mahdi Al-Kaisi, 2005
Figure 23	p.20	Troeh and Thompson, 1993 in Smith and Doran, 1996
Figure 24	p.22	Mahdi Al-Kaisi, 2015
Figure 25	p.22	Hobbie, 2015
Figure 26	p.23	USDA-NRCS
Photo	p.25	Strip-tillage (ST) and Conventional-tillage (CT), Randy Haarberg, Orthman
Photos	p.45	Courtesy of USDA NRCS

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Protect soil heath with conservation practices.

Healthy soil with earthworm

Conservation buffers and terraces

Contour farming and conservation tillage

Grass waterway

Cover crops

Residue on the surface

Managing Soil Health—To sustain plant, animal, and human life and maintain or enhance ecosystems services