Chapter Two
The Biology of Soil Structure

Soil – A Complex Environment

The Basic Stuff of Soils

Soil has five basic constituents:

- minerals
- gasses
- water
- organic materials
- microorganisms

Minerals usually comprise just under half of the volume of soil. Minerals in soil are generally the result of weathering, which is the process of gradual breakdown of rock by the acids and salts contained in rain and soil water, substances released by plant roots, soil animal activity, ice formation, and other impacts resulting from changes in temperature and moisture.

The other half (roughly) of the volume of healthy soils consists of the spaces between soil particles, which are filled to varying degrees with water and air.

The fraction of soil occupied by organic matter is usually measured by weight and ranges generally from 1 to 10 per cent (higher in organic soils). The last category, microorganisms, come in at less than 1 per cent by volume.

Even though the volume occupied by organisms is relatively small, we will see later in this primer that they play a very important role in how all of the other materials are managed and utilized in the underground community.

Bathtubs and Basketballs

Dr. Rattan Lal, one of the world's foremost soil scientists, uses the following analogy to describe how the various mineral components of soil relate in size. Think about a bathtub full of basketballs. In relative terms, this is what a soil comprised entirely of sand (e.g., a beach) is like. The large sand particles (0.5-2.0 mm) leave so much space between them that water flows right through the soil and runs out along whatever hard surface underlies it. Now imagine that the tub is filled with marbles (the average size of silt particles, which lie between .002 and 0.5 mm, relative to sand). This would slow the water down, but would not stop it running though. Finally, imagine the tub filled with tiny beads, ranging in size from a pea (at the large end) to less than the period at the end of this sentence (in real terms, from .002 mm down to the size of bacteria). Now we would see some serious impediment to water flow. Perhaps, if the smallest beads were very tiny, and if they filled in all of the spaces between the larger beads, the flow might be blocked completely.

Soils, of course, are at a much smaller scale, so it is easy to imagine how even loam soils, which are considered the best for agriculture, can become compacted. A good loam soil has a rough composition of 40 per cent sand, 40 per cent silt, and 20 per cent clay. Settling of the particles into a compacted state can be due to several factors, including the pull of gravity, the lateral and downward movement of water as it flows through soil, and downward pressure from the wheels of farm equipment and the hooves of grazing animals. These forces and others can cause silt to fill the spaces between the sand particles and tiny clay particles to fill the spaces between them both, creating a solid barrier that water (and plant roots) cannot penetrate. Fortunately, nature has a way to prevent this from happening, via the creation of what is called soil structure.

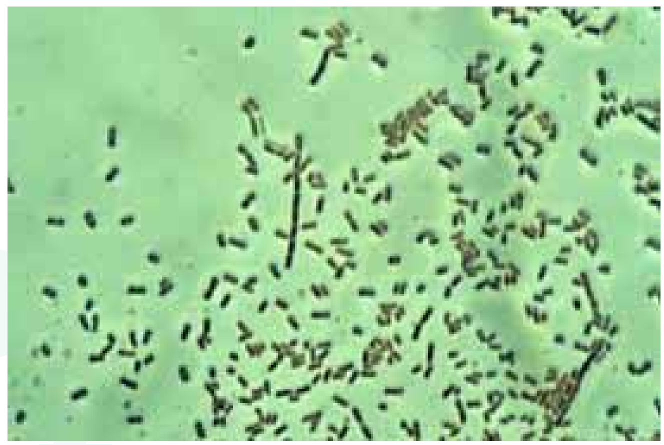
Soil Structure and Water Management

What could be more important than managing water? Soil is the filter through which much of our rainwater passes on the way back to the ocean; the soil slows its progress, holds it and cleans it. If the soil has structure, it lets the rain infiltrate easily, then absorbs and holds it like a sponge, so that plants of all kinds can access it as they need it. Alternatively, when soil is compacted, it rejects much of the rainwater and flooding often ensues. Compacted soil can't accept or hold much water, so plant life is extremely limited and unproductive. For natural ecosystems, water is the essence of life and soil is the undeniable manager of that essence.

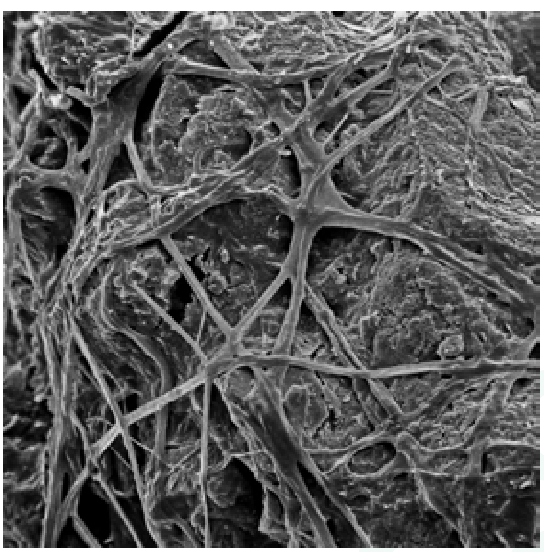
For farmers, water is a major key to productivity. No amount of nutrient will grow a good crop if water is lacking. Moreover, farmers have long understood that for soil to hold significant amounts of water, it needs to have good amounts of organic matter. However, the specific processes within the soil that open it up and create the structure that allows better infiltration of rainfall and increased water-holding capacity have not been that well understood in the past. We now know that good soil structure is the direct result of stable soil aggregate formation and that to understand that process, we have to go back to talking about the largely invisible creatures of the soil food web.

Soil Aggregate Formation

Soil aggregation processes are primarily run by the microbes in the soil food web. Although tiny mineral particles (particularly clay) do form small aggregates due to chemical attractions, the real work of making soil come together in clumps falls to the various forms of soil life. Bacteria secrete glues as a matter of survival. It allows them to stick themselves to a particle, be it mineral or organic, so that they are not washed away with the rainwater as it passes through the soil. When you look in a microscope at a soil sample (see **Figure 21**), you will see some bacteria floating free (shaken free during the sample preparation, for the most part), but many are attached to something. The glues that they produce to do this work also benefit the entire community, as they result in the establishment of micro-aggregates, which are tiny clumps of minerals, organic residues, and living microbes.



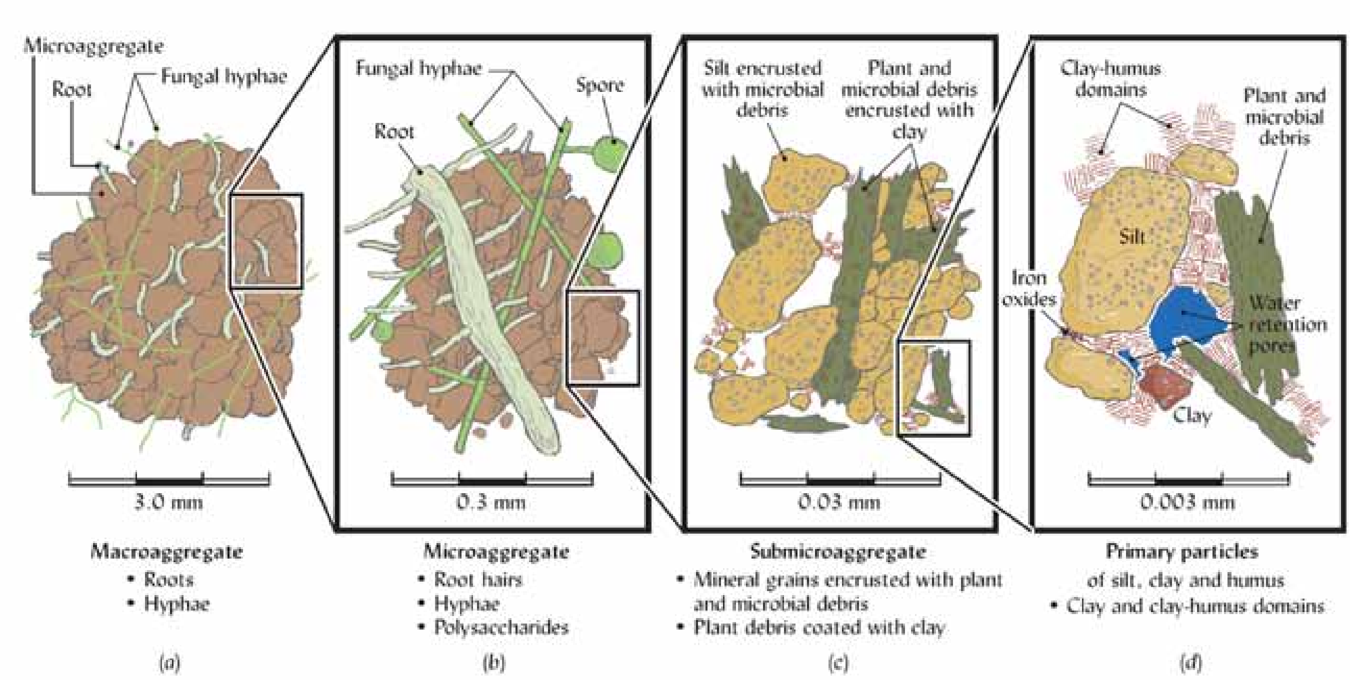
Bacteria under microscope
(Figure 21)
Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society



Fungal hyphae & macroaggregates
(Figure 22)
Source: Eickhorst, Thilo & Tippkoetter, Rolf. Micropedology – The hidden world of soils. University of Bremen, Germany

Earthworms are also good at this job, as they also secrete a sticky substance through their skins. As they travel their underground routes they slough off mixtures of gluey slime, hitch-hiking microbes, and various soil particles, basically leaving aggregate components in their wake. Given these facts, it makes sense that the more bacteria and earthworms you have in your soil, the more potential your soil has for good texture, or aggregation.

The *stable soil aggregate story*, however, does not end there; this is where fungi come in and really change the game. Fungal hyphae are always growing, moving through the soil in search of nutrients and water. Some of these hyphae twine themselves around groups of micro-aggregates, pulling them together into larger clumps (see **Figure 22**). In addition, hyphae of mycorrhizal fungi slough off a substance called glomalin, which is both sticky and resistant to degradation by other microbes. Fungal hyphae only live a few weeks, but new ones are constantly growing to replace them. As these processes go on all the time in healthy soil, larger (macro) aggregates are constantly being dissembled and then re-formed.



Schematic of soil aggregate *(Figure 23)*
Source: Cornell University Cooperative Extension, Northern NY Field Crops Team

These aggregates are of different shapes and sizes and their variability and relatively large size creates spaces between them (see **Figure 23**). These are the pore spaces that allow for water storage and also promote aerobic conditions (air can enter a well aggregated soil more easily than a compacted one, due to the pore spaces and the connections between them). In addition, the various glues involved are hydrophobic, that is, insoluble in water and resistant to breakdown in wet conditions. This is extremely important given their role in water storage.

This aggregate-forming process within soils is enhanced as organic matter is increased. This is mainly because soil organic matter supports soil life, and soil life creates the aggregates. This organic matter also absorbs and holds water, but it is the aggregation that is key to water management. Lately, scientists have determined that rates of aggregation increase directly with the increase in the amount of fungi present in the soil. These studies have shown a direct correlation between the amount of fungal biomass in soils and the levels of stable soil aggregates.

Rainfall simulator *(Figure 24)*
Source: OMAFRA

The Benefits of Good Soil Structure

Seasoned soil-health practitioners find that their soils allow for the complete infiltration of even very heavy rainfalls and that the water storage capacity of their soils increases greatly (see **Figure 24** –a rainfall simulator can demonstrate the infiltration rates of soils under different types of management). Droughts are much less of a problem for farmers with well aggregated soils. While their yields generally tend to be higher than the regional average, they are always much higher than average in dry years. This is because so much water is stored in well-structured soil and is therefore always available when the crop needs it.

Water holding capacity, however important, is only one of the many benefits of well aggregated soil. Some of these benefits are mainly experienced by farmers; others are experienced by society at large, as environmental improvements. The following are some of the key benefits to farmers and to the environment:

- In addition to drought resistance, benefits of good soil structure to farmers include:
  - o Better retention of valuable inputs, such as fertilizer and pesticides. Water running off compacted soils takes a large percentage of these inputs with it.
  - o Less standing water and flooding (see **Figure 25**).
  - o Better plant growth. Good soil structure allows for better root growth and penetration,
which in turn results in better nutrient uptake by plants.
  - o More beneficial soil functions (nutrient turnover, disease suppression, etc.). As we will see in later chapters, these functions depend on a large, diverse, and healthy soil food web. The community of organisms that make up this web in turn depend on adequate water, oxygen, and space to live – all of which require good soil structure.
  - o Overall better profitability. If farmers can reduce input costs (including labour and fuel) while maintaining or exceeding their yield, they will make more money. Successful soil-health practitioners always state that good soil structure is a key to their profitability.

Standing water in fields *(Figure 25)*
Source: OMAFRA

- Benefits to society at large include:
  - o Food security. As our climate changes, resiliency in the face of those changes becomes very important. A well structured soil is more resilient to extremes of heat and precipitation, able to maintain productivity in cool, hot, dry, and wet seasons.
  - o Less risk of flooding. Always a concern in low-lying areas prone to extreme rainfall, flooding has become much more common almost everywhere as our climate has warmed. This is likely to get worse, rather than better, and soils that allow more infiltration and hold more water can have a big impact on flooding, significantly reducing its negative impacts.
  - o Less pollution. Nutrients that are valuable in the soil become a source of pollution in streams, rivers, lakes and even oceans (see **Figure 26**). Well aggregated soils reduce pollution by eliminating run-off and through their greater capacity to hold on to both water and nutrients.
  - o Enhanced biodiversity. The organisms of the soil food web are at the base of the entire planet's food web. Fewer soil insects and earthworms means less to eat for birds and small mammals. Less life in the soil translates into less diversity of life above ground.

Lake Erie Algal Bloom *(Figure 26)* *Source:* NASA

Summary

Soil consists of a mixture of minerals, air, water, organic matter, and living organisms. The mineral components (about 50 per cent by volume) are classified by size, with diameters ranging from relatively large sand particles (up to 2 mm) to microscopic clay particles (a few microns). Gravity and other physical forces, such as water movement and pressure from the tires of farm equipment, can cause these particles to settle in such a way as to fill in all the spaces between them, restricting the flow of air and water and reducing the living space available to soil organisms. This is known as compacted soil.

Fortunately, natural processes work to prevent this compaction by developing what we call soil structure. Clumps of soil particles (both mineral and organic) of different sizes and shapes are formed into aggregates. These clumps do not fit together evenly, resulting in spaces between them called pore spaces. It is in these spaces that water and air are held and where the living organisms of the soil food web reside. We now know that these aggregates are in fact largely created by soil microbes, which secrete water-resistant glues that hold the particles together. Fungi in particular play a very important role because of their ability to pull smaller aggregates together into larger ones, called macro-aggregates.

A well-aggregated soil (see **Figure 27**) provides both farmers and society at large with many benefits. Farmers find that their soils can infiltrate and hold much more water, resulting in less run-off of valuable inputs, greater drought resistance, higher yields, and increased profitability. Society benefits from a cleaner environment, greater food security, less risk of flooding, and the protection of biodiversity.

Comparison of well aggregated soil (left) to soil that is not (right) *(Figure 27)*
Source: Mel Luymes and Adam Ireland