Role of Soil Bacteria: Update and Revision

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Microbes in the soil are directly tied to nutrient recycling especially carbon, nitrogen, phosphorus, and sulfur. Bacteria are a major class of microorganisms that keep soils healthy and productive.

Bacteria Characteristics

Ingham (2009, pg. 18) states that "Bacteria are tiny one-celled organisms generally 4/100,000 of an inch wide (1 µm). A teaspoon of productive soil generally contains between 100 million and 1 billion bacteria. That is as much mass as two cows per acre. A ton of microscopic bacteria may be active in each acre". While bacteria may be small, they make up both the largest number and biomass (weight) of any soil microorganism. Figure 1 shows ciliate protozoa consuming bacteria.

Bacteria are similar in size to clay soil particles (<.2µm) and silt soil particles (2-50µm). They grow and live in thin water films around soil particles and near roots in an area called the rhizosphere. Bacteria's small size enables them to grow and adapt more rapidly to changing environmental conditions than larger, more complex microorganisms like fungi.

Most soils are simply a graveyard for dead bacteria cells. Bacteria are so simple in structure that they have often been called a bag of enzymes and/or soluble bags of fertilizer (Dick, R., 2009,). Since bacteria live under starvation conditions or soil water stress, they reproduce quickly when optimal water, food, and environmental conditions occur. Bacteria population may easily double in 15-30 minutes. Flourishing microbial populations increase soil productivity and crop yields over time.

Bacteria Classification

Most bacteria are classified into one of the following four categories.

Bacteria shape

When scientist started first classifying bacteria, they started by looking at their basic shape. Bacteria generally have three major shapes: rod, sphere, or spiral. Actinomycetes are still classified as bacteria but are similar to fungi except they are smaller in size. Classifying bacteria by shape is complex because many bacteria have different shapes and different arrangements.

Figure 1: Close up view of a ciliate (protozoa) with various bacteria in the background. Ingham, (2009, pg. 18) states “A ton of microscopic bacteria may be active in each acre of soil.” Photographed by Tim Wilson. Used with Permission and ALL rights reserved.

Aerobic and Anaerobic Bacteria

Most microbes are generally inactive and may only have short burst of soil activity. Soil oxygen levels often determine soil bacteria activity (Dick, W., 2009). Most soil bacteria prefer well oxygenated soils and are called aerobic bacteria and use the oxygen to decompose most carbon compounds. Examples of aerobic bacteria include the *Aerobacter* genus which is widely distributed in the soil and actinomycetes bacteria genus *Streptomyces* which give soil its good “earthy” smell (Lowenfels & Lewis, 2006).

Anaerobic bacteria prefer and some require an environment without oxygen. Anaerobic bacteria are generally found in compacted soil, deep inside soil particles (microsites), and hydric soils where oxygen is limiting. Many pathogenic bacteria prefer anaerobic soil conditions and are known to outcompete or kill off aerobic bacteria in the soil. Many anaerobic bacteria are found in the intestines of animals and are associated with manure and bad smells (Lowenfels & Lewis, 2006).

Gram Negative and Gram Positive Bacteria

When a staining agent is used in the lab, bacteria can be classified as "gram negative" or "gram positive". The staining agent attaches to the bacteria's cell walls. Gram negative bacteria are generally the smallest bacteria and are sensitive to drought and water stress. Gram positive bacteria are much larger in size, have thicker cell walls, negative charges on the outside cell wall surface and tend to resist water stress (Dick, R., 2009*). Bacteroides* are anaerobic gram negative bacteria that live in the gut of man and animals. *Listeria* is a gram positive aerobic rod shaped bacteria found in contaminated food.

Other Bacteria Classifications

Another way to classify bacteria is by their growth and reproduction. Autotrophic bacteria (also called autotrophs) process carbon dioxide to get their carbon. Some autotrophic bacteria directly use sunlight and carbon dioxide to produce sugars, while others depend on other chemical reactions to obtain energy. Algae and cyanobacteria are some examples of autotrophic bacteria. Heterotrophic bacteria obtain their carbohydrates and/or sugars from their environment or the living organism or cell they inhabit. Examples include *Arthrobacter* bacteria involved in nitrogen nitrification (Sylvia et al., 2005).

With new advances in DNA sequencing, most scientists are classifying bacteria based on the type of environment in which they inhabit. Bacteria can live in extreme environments like hot springs for sulfur bacteria or in extreme cold as in ice water in the Artic. Bacteria may also be classified by living in a highly acidic versus alkaline environment, aerobic versus anaerobic, or autotrophic versus heterotrophic environment (Dick, R., 2009).

Bacteria Functions/ Groups

Bacteria perform many important ecosystem services in the soil including improved soil structure and soil aggregation, recycling of soil nutrients, and water recycling. Soil bacteria form microaggregates in the soil by binding soil particles together with their secretions. These microaggregates are like the building blocks for improving soil structure. Improved soil structure increases water infiltration and increases water holding capacity of the soil (Ingham, 2009).

Bacteria perform important functions in the soil, decomposing organic residues from enzymes released into the soil. Ingham (2009) describes the four major soil bacteria functional groups as decomposers, mutualists, pathogens, and lithotrophs. Each functional bacteria group plays a role in recycling soil nutrients.

The Decomposers consume the easy to digest carbon compounds and simple sugars and tie up soluble nutrients like nitrogen in their cell membranes. Bacteria dominate in tilled soils but they are only 20-30 percent efficient at recycling carbon (C). Bacteria are higher in nitrogen (N) content (10-30 percent nitrogen, 3 to 10 C:N ratio) than most microbes (Islam, 2008).

Of the mutualistic bacteria, there are four bacteria types that convert atmospheric nitrogen (N_2) into nitrogen for plants. There are three types of soil bacteria that fix nitrogen without a plant host and live freely in the soil and these include *Azotobacter, Azospirillum, and Clostridium*. The *Rhizobium* bacteria (gram negative rod shaped bacteria) species associate with a plant host: legume (alfalfa, soybeans) or clover (red, sweet, white, crimson) to form nitrogen nodules to fix nitrogen for plant growth. The plant supplies the carbon to the *Rhizobium* in the form of simple sugars. *Rhizobium* bacteria take nitrogen from the atmosphere and convert it to a form the plant can use. For plant use, the atmospheric nitrogen (N_2) or reactive nitrogen combines with oxygen to form nitrate (NO_3^-) or nitrite (NO_2^-) or combines with hydrogen to produce ammonia (NH_3^+) or ammonium (NH_4^+) which are used by plant cells to make amino acids and proteins (Lowenfels & Lewis, 2006). Figure 2 showsnitrogen fixing bacteria.

Many soil bacteria process nitrogen in organic substrates, but only nitrogen fixing bacteria can process the nitrogen in the atmosphere into a form (fixed nitrogen) that plants can use. Nitrogen fixation occurs because these specific bacteria produce the nitrogenase enzyme. Nitrogen fixing bacteria are generally widely available in most soil types (both free living soil species and bacteria species dependent on a plant host). Free living species generally only comprise a very small percentage of the total microbial population and are often bacteria strains with low nitrogen fixing ability (Dick, W., 2009).

Nitrification is a process where nitrifying bacteria convert ammonia (NH_4^+) to nitrite (NO_2^-) and then to nitrate (NO_3^-). Bacteria and fungi are typically consumed by protozoa and nematodes and the microbial wastes they excrete is ammonia (NH_4^+) which is plant available nitrogen. Nitrite bacteria (*Nitrosomonas* spp.) convert the ammonia into nitrites (NO_2^-) and nitrate bacteria (*Nitrobacter* spp.) may then convert the nitrites (NO_2^-) to nitrates (NO_3^-) Nitrifying bacteria prefer alkaline soil conditions or a pH above 7 (Lowenfels & Lewis, 2006). Both nitrate and ammonia are plant available forms of nitrogen, however; most plants prefer ammonia because the nitrate has to be converted to ammonia in the plant cell in order to form amino acids.

Denitrifying bacteria allow nitrate (NO_3^-) to be converted to nitrous oxide (N_2O) or dinitrogen (N_2) (atmospheric nitrogen). For denitrification to occur, a lack of oxygen or anaerobic conditions must occur to allow the bacteria to cleave off the oxygen. These conditions are common in ponded or saturated fields, compacted fields, or deep inside the microaggregates of soil where oxygen is limited. Denitrifying bacteria decrease the nitrogen fertility of soils by allowing the nitrogen to escape back into the atmosphere. On a saturated clay soil, as much as 40 to 60 percent of the soil nitrogen may be lost by denitrification to the atmosphere (Dick, W., 2009).

Figure 2: Nitrogen fixing Rhizobium bacteria form nodules on a soybean root. Photo by Randall Reeder. Used with permission and All Rights Reserved.

Pathogenic bacteria cause diseases in plants and a good example are bacteria blights. Healthy and diverse soil bacteria populations produce antibiotics that protect the plants from disease causing organisms and plant pathogens. Diverse bacteria populations compete for the same soil nutrients and water and tend to act as a check and balance system by reducing the disease causing organism populations. With high high microbial diversity, soils have more nonpathogenic bacteria competing with the pathogenic bacteria for nutrients and habitat (Lowenfels & Lewis, 2006). *Streptomycetes* (actinomycetes) produce more than 50 different antibiotics to protect plants from pathogenic bacteria (Sylvia et al., 2005).

Lithotrophs (*chemoautotrophs)* get their energy from compounds other than carbon like (nitrogen or sulfur) and include species important in nitrogen and sulfur recycling. Under well-aerated conditions, sulfur-oxidizing bacteria make the sulfur more plant available while under saturated (anaerobic, low oxygen) soil conditions, sulfur reducing bacteria make sulfur less plant available.

Actinomycetes have large filaments or hyphae and act similar to fungus in processing soil organic residues which are hard to decompose (chitin, lignin, etc.). When farmers plow or till the soil, actinomycetes release “geosmin” as they die which gives freshly turned soil it characteristic smell. Actinomycetes decompose many substances but are more active at high soil pH levels (Ingham, 2009). Actinomycetes are important in forming stable humus; which enhances soil structure, improves nutrient storage, and increases water retention.

Soil Benefits from Bacteria

Bacteria grow in many different microenvironments and specific niches in the soil. Bacteria populations expand rapidly and the bacteria are more competitive when easily digestible simple sugars are readily available around in the rhizosphere. Root exudates, dead plant debris, simple sugars, and complex polysaccharides are abundant is this region. About 10 to 30 percent of the soil microorganisms in the rhizosphere are actinomycetes, depending on environmental conditions (Sylvia et al., 2005).

Many bacteria produce a layer of polysaccharides or glycoproteins that coats the surface of soil particles. These substances play an important role in cementing sand, silt, and clay soil particles into stable microaggregates that improve soil structure. Bacteria live around the edges of soil mineral particles especially clay and associated organic residues. Bacteria are important in producing polysaccharides that cement sand, silt, and clay particles together to form microaggregates and improve soil structure (Hoorman, 2011). Bacteria do not move very far in the soil, so most movement is associated with water, growing roots or hitching a ride with other soil fauna like earthworms, ants, spiders, etc. (Lavelle & Spain, 2005).

In general, most soil bacteria do better in neutral pH soils that are well oxygenated. Bacteria provide large quantities of nitrogen to plants and nitrogen is often lacking in the soil. Many bacteria secrete enzymes in the soil to makes phosphorus more soluble and plant available. In general bacteria, tend to dominate fungi in tilled or disrupted soils because the fungi prefer more acidic environments without soil disturbance. Bacteria also dominate in flooded fields because most fungi do not survive without oxygen. Bacteria can survive in dry or flooded conditions due to their small size, high numbers, and their ability to live in small microsites within the soil where environmental conditions may be favorable. Once the environmental conditions around these microsites become more favorable, the survivors quickly expand their populations (Dick, W., 2009). Protozoa tend to be the biggest predators of bacteria in tilled soils (Islam, 2008).

In order for bacteria to survive in the soil, they must adapt to many microenvironments. In the soil, oxygen concentrations vary widely from one microsite to another. Large pore spaces filled with air provide high levels of oxygen, which favors aerobic conditions, while a few millimeters away, smaller micropores may be anaerobic or lack oxygen. This diversity in soil microenvironments allows bacteria to thrive under various soil moisture and oxygen levels, because even after a flood (saturated soil, lack of oxygen) or soil tillage (infusion of oxygen) small microenvironments exist where different types of bacteria and microorganisms may live to repopulate the soil when environmental conditions improve.

Natural succession happens in a number of plant environments including in the soil. Bacteria improve the soil so that new plants can become established. Without bacteria, new plant populations and communities struggle to survive or even exist. Bacteria change the soil environment so that certain plant species can exist and proliferate. Where new soil is forming, certain photosynthetic bacteria start to colonize the soil, recycling nitrogen, carbon, phosphorus, and other soil nutrients to produce the first organic matter A soil that is dominated by bacteria usually is tilled or disrupted and has higher soil pH and nitrogen available as nitrate, which is the perfect environment for low successional plants called weeds (Ingham, 2009).

As the soil is disturbed less and plant diversity increases, the soil food web becomes more balanced and diverse, making soil nutrients more available in an environment better suited to higher plants. Diverse microbial populations with fungus, protozoa, and nematodes keep nutrients recycling and keep disease causing organisms in check.

Summary

Bacteria are the smallest and most hardy microbe in the soil and can survive under harsh or changing soil conditions. Bacteria are only 20–30% efficient at recycling carbon, have a high N content (10 to 30% N, 3–10 C:N ratio), a lower C content, and a short life span. There are basically four functional soil bacteria groups including decomposers, mutalists, pathogens, and lithotrophs. Decomposer bacteria consume simple sugars and simple carbon compounds, while mutualistic bacteria form partnerships with plants including the nitrogen-fixing bacteria *(Rhizobia)*. Bacteria can also become pathogens to plants and lithotrophic bacteria convert nitrogen, sulfur, or other nutrients for energy and are important in nitrogen cycling and pollution degradation. Actinomycetes are classified as bacteria but are very similar to fungus and decompose recalcitrant (hard to decompose) organic compounds. Bacteria have the ability to adapt to many different soil microenvironments (wet vs. dry, well oxygenated vs. low oxygen). They also have the ability to alter the soil environment to benefit certain plant communities as soil conditions change.

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