THE POSITIVE SIDE OF OUR SOILS

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The initial reaction of farmers and gardeners when they hear the words "bacteria, fungi, nematodes" is to reach for the closest bottle of pesticide and rush off to their fields to apply that pesticide in abundance. Fortunately, only a very small portion of microorganisms present in a healthy soil causes damage to crops, whereas the biggest portion of microorganisms in healthy soils actually benefits our crops (and us) in ways that we are not even aware of.

In the July edition of the ACT Newsletter, we talked about the sensitivity of the biological (living) component of our soils to changes inside and around the soil environment. We also referred to the co-existence of the good (beneficial) and bad/disease-causing (pathogenic) soil microorganisms. In this edition, we will be having a closer look at the beneficial soil microorganisms.

The sensitive balance

Soil microorganisms such as bacteria (Figure 1a, b), fungi (Figure 2a, b), yeasts (Figure 3) and nematodes (Figure 4) work belowground to break down contaminants, decompose organic material (also called mineralization), mediate carbon, phosphorous, nitrogen and sulfur cycling, thus contributing to soil fertility and quality. Since chemical elements and minerals are required to fulfill numerous functions in the soil ecosystem, these elements and minerals need to be cycled continuously throughout the ecosystem by means of various interrelated biological processes. Microbial communities are therefore crucial in nutrient cycling in order to unlock essential elements from complex organic compounds that could be taken up by other organisms and plant roots for growth. This intricate relationship between microorganisms and minerals enhances effective nutrient cycling which also contributes to the resilience of soils by supporting soil microbial diversity and activity. It is a fact that different soil microorganisms do not function in isolation, but are also dependent on other microorganisms. Each of these diverse microorganisms play a vital role in the belowground foodweb where they support and sustain each other directly, or indirectly. When herbicides, fungicides, nematicides or other indiscriminate soil sterilization techniques are implemented, large parts of the soil foodweb are destroyed, creating an imbalance in the foodweb. Unfortunately, it is usually the pathogenic microorganisms that return first after such a disturbance – thriving in the absence of enemies and competitors that were also annihilated in the sterilization process. Now, let's have a look behind the scenes at the integral role that these vulnerable enemies and competitors against pathogens play in the soil ecosystem.

Behind the scenes

The number of soil microorganisms, especially bacteria, are 10-100 times more in the thin layer surrounding the root (rhizosphere) than in bulk soil due to the presence of nutrient-rich root exudates. This will consequently lead to increased microbial diversity and activity which will force soil microorganisms to compete, collaborate, or parasitize for available food sources. It is thus evident that direct and indirect relationships between plants and associated soil microbial communities are inevitable.

Taking into consideration that 50,000 bacteria can fit on a pinhead, it is easy to comprehend that a teaspoon of healthy soil might contain between 100 million and 1 billion bacteria, with approximately 25,000 different types of bacteria in the same teaspoon! The main aim of soil bacteria is to, directly or indirectly, cycle nutrients in the soil. Some groups of bacteria also have "added benefits" that benefit plants in other ways than merely cycling nutrients.

Plant growth-promoting rhizobacteria (PGPR)

PGPR is a term used to describe root-colonizing bacteria that form a relationship beneficial to both the bacteria and the plant. Depending on their role in the rhizosphere, PGPR can generally be divided in to two groups: the plant growth-promoting PGPR, and the biocontrol PGPR. As the names suggest, the former group promotes plant growth and includes free-living bacteria, e.g., *Azotobacter* and *Azospirillum* that form non-symbiotic nitrogen fixation relationships with many non-leguminous plants, and root nodule-forming bacteria that form very specific symbiotic relationships with leguminous plants (e.g., *Rhizobium*). The biocontrol PGPR represent specific root bacteria (rhizobacteria) with the ability to suppress or decrease soilborne diseases, e.g., *Bacillus subtilis*, *Bacillus thuringiensis*, *Pseudomonas fluorescens*, and certain *Streptomyces* and *Lactobacillus* species.

Most free-living growth-promoting PGPR influence plant growth and crop yield directly by synthesizing plant hormones that enhance plant growth by altering the plant's metabolism and root surface area and length to increase the absorption of water and minerals, consequently leading to healthier plants. Other growth-promoting PGPR contribute to crop growth and yield by solubilizing essential minerals such as phosphorous, calcium and potassium, fixing atmospheric nitrogen, and synthesizing siderophores (Greek: "iron carrier") which bind iron from the soil and transporting it to the plant roots.

The biocontrol PGPR has a wide range of indirect means to enhance plant growth by suppressing plant diseases. Some PGPR produce specific enzymes that dissolve the cell walls of pathogenic fungi, while others produce antibiotics. A typical example of biocontrol PGPR is the suppression of fusarium wilt by a specific strain of the bacterium *Pseudomonas fluorescens* that resulted in a 40% yield increase in radish. Other PGPR increase competition for minerals by binding iron, making it inaccessible to, thus suppressing, soilborne plant pathogens. PGPR-mediated induced systemic resistance in host plants has also been detected against several fungal pathogens.

Biological Nitrogen Fixation (BNF)

With nitrogen (N) often being the most limiting nutrient in soil for plant growth, it is not surprizing that N-fertilizers rank the highest among chemical fertilizers applied to maximize crop yields. Unfortunately, it is very expensive, frequently unavailable in certain countries, and the cause of major environmental pollution. This is where BNF becomes the inexpensive and environmentally-friendly alternative to chemical N-fertilizers. Root-nodule bacteria, e.g., *Rhizobium* convert atmospheric nitrogen into a form that can be easily utilized by the leguminous plants. Frankly, the sustainability of many leguminous food crops, green manure legumes and forage depend mainly on their ability to form a symbiotic relationship with specific rhizobia. These rhizobia, growing in the rhizosphere of a specific legume host, recognize specific compounds (i.e., flavonoids) secreted by the roots of the host plant. The flavonoids activate the production of nodulation factors in the rhizobia, leading to the host plant's root hairs "recognizing" the rhizobia and curling around the rhizobia. The rhizobia enter into the host plant's root cells, multiply, and eventually form the actual root nodule. This symbiotic relationship has the ability to convert atmospheric nitrogen into a renewable source of agricultural nitrogen within the range of 100-360 kg nitrogen per hectare per year; equivalent to 30-80 kg fertilizer nitrogen per hectare. Through this relationship, the soil's nitrogen-levels are maintained, serving as an environmentally-friendly sustainable substitute for chemical nitrogen fertilizers.

Apart from the beneficial bacteria, beneficial fungi also naturally occur in abundance in healthy soils. A single gram of healthy soil might contain up to 1 million fungi with a biomass of 100-1,500 g/m^2, whereas a teaspoon of healthy forest soil may hold more than 1,600 meters of fungi threads ("fungal hyphae"). Fungi usually increase in diversity with the application of permanent soil mulch cover in combination with minimum soil disturbance. Fungi are responsible for the degradation and conversion of complex molecules in plant mulches to smaller nutrients and elements that are more readily available for conversion and utilization by bacteria.

Mycorrhiza

Probably one of the most well-known mutualistic interrelationships that exist in ecosystems, is called mycorrhiza (Greek: *mycos* = "fungi", *rhiza* = "root"). This relationship exists because of the integration of a soilborne fungus' hyphae with the roots of more than 80% of higher plants and ferns (Figure 5). Through this integrated association, the surface area of plant roots is increased (Figure 6), leading to increased uptake of water and nutrients such as phosphorous and nitrogen from nutrient-deficient soils, resistance to plant pathogens, and increased tolerance to toxins and other environmental variables. In return, the mycorrhizal fungi escape competition for food with other soil microorganisms by receiving nutrients from the host plant.

Other beneficial fungi such as *Trichoderma harzianum* also occur naturally in almost all soils and can be applied as an inoculant to serve as a biocontrol agent against certain pathogenic fungi, as well as certain pathogenic nematodes. Certain fungi, called nematode trapping fungi, are carnivorous fungi with specialized structures and methods to successfully trap and consume nematodes. A defensive mutual relationship has also been found to exist between certain beneficial fungi and grasses, where the fungi live their entire lives inside the host plant, without affecting the host plant negatively. The fungi can assist the host plant in overcoming environmentally stressful situations such as high soil salinity, drought, and consequent low nutrient availability. In response, the host plant provides the fungi with nutrients and protection from the sun's harmful radiation. Some fungi such as the Chinese caterpillar fungus, which parasitizes on insects, are used to control insects that are responsible for crop losses, while other beneficial fungi simply outcompete the pathogenic fungi for nutrients, water, and space.

Yeasts

Besides bacteria and fungi in the soil, several yeasts (Figure 3) also occur naturally in soils where they interact with the living and non-living components of the ecosystem. Besides their role in mineralization of organic material and serving as a source of nutrients to various soil microorganisms, they also play a role in soil aggregate formation and soil structure maintenance. Certain yeasts are suspected to play roles in phosphate-solubilization, and in the nitrogen and sulphur cycles in order to make these minerals more easily available to plant roots. Yeasts are also being studied as potential plant-growth promoters and soil conditioners in sustainable agriculture. Recent research has shown improved growth of blue lupin (*Lupinus angustifolius*) treated with the yeast *Cryptococcus laurentii*, supported by increased biological nitrogen fixation efficiency. The yeast *Rhodotorula mucilaginosa*, on the other hand, has been shown to be an effective biocontrol agent against fungi causing tomato stem canker disease and cucumber stem blight.

Soil Nematodes

Nematodes ("roundworms") are wormlike microscopic organisms, generally 0.3-5.0 mm long, inhabiting a very broad range of environments owing to their wide range of feeding habits (Figure 7). In agriculture, 90% of nematodes are found in the top 15 cm of the soil, and the numbers of soil-inhabiting numbers can be in the millions, commonly with more than 30 different groups of nematodes present. Nematodes are usually synonymous with immense crop losses, but they also consist of a free-living component consisting of nematodes feeding on bacteria (bacterial-feeding nematodes), fungi (fungal-feeding nematodes), other nematodes (predatory nematodes) (Figure 8), and many other different soil organisms (omnivorous nematodes).

Beneficial nematodes contribute to the functioning of a soil ecosystem by suppressing fungi hyphae growth, controlling bacterial populations, killing insect pests and other nematodes. Nematodes feeding on bacteria, for example, may consume up to 5,000 bacteria per minute! Due to their feeding interactions, nematodes play important roles in nutrient mineralization. Nematodes also indirectly enhance decomposition and nutrient cycling by feeding and stimulating inactive bacterial and fungal populations. Without beneficial nematodes, nutrients such as nitrogen can remain inside bacteria and fungi, and unavailable for uptake by plant roots.

Nematodes have also been shown to be indicators of healthy soils. The numbers and types of nematodes present in a soil reflect changes in the microorganisms, i.e., bacteria, fungi, they consume, as well as the soil's chemical and physical environment. Not only do populations of predatory and omnivorous nematodes indicate the impact of pollutants and other disturbances on the soil biology, but also the ability of a soil to suppress pathogenic organisms.

Concluding remarks

There is no doubt concerning the important role beneficial microorganisms play in the soil ecosystem. The total destruction of crop pests and plant pathogens with the aid of pesticides, fungicides or resistant-induced mechanisms not only increases resistance in pathogen populations, but it also leaves the plant defenseless against pesticide-resistant insects and pests. Studying and understanding the intrinsic ecological balance – even between beneficial and pathogenic microorganisms – will lead to new approaches in agriculture to improve sustainability and increase crop production.

Figures in the articles Captioned

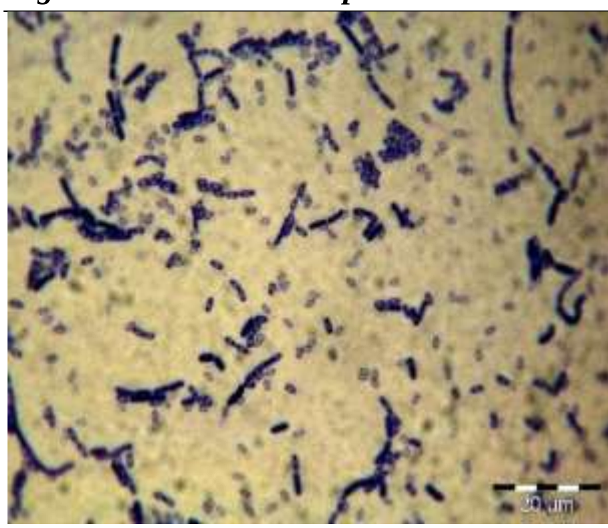

Figure 1a: Microscope photo of *Bacillus thuringiensis*, a beneficial bacteria found naturally in soils. Credit: Dr. A. Hassen, ARC-PPRI.

Figure 1b: Bacteria grown on artificial media in petri dishes. Credit: Dr. A. Hassen, ARC-PPRI.

Figure 2a: Fungi decomposing tree bark. Credit: Ms. W. Kriel, Starke Ayres.

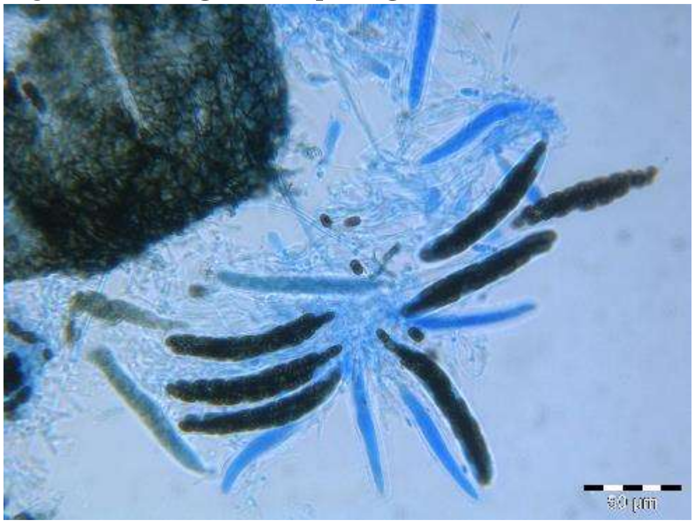

Figure 2b: Fungi "survival spores" under the microscope. Credit: Dr. E. van der Linde, ARC-PPRI.

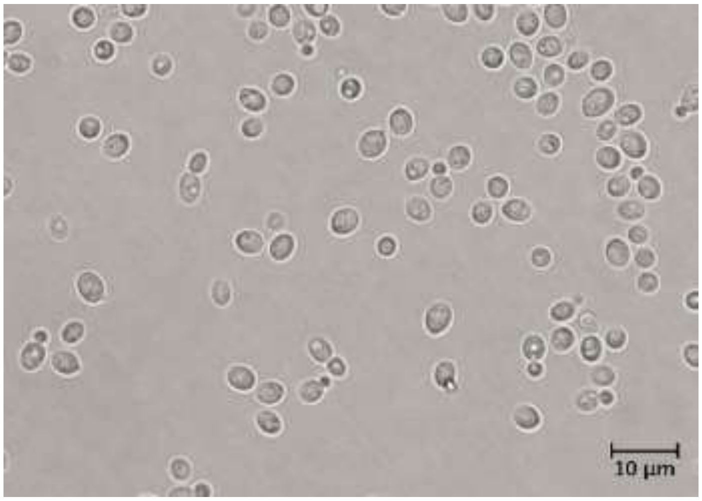

Figure 3: Microscope photo of a yeast found naturally in soil. Credit: Ms. L. Moller, University of Stellenbosch.

Figure 4: Microscope photo of the adults, juveniles, and egg stages of free-living (beneficial) soil nematodes.

Figure 5: Photo of the mutual beneficial relationship between plant roots and the mycorrhizal fungi (thin white "threads").
Credit: https://gardenofeaden.blogspot.co.za/2009/05/what-are-mycorrhizal-fungi.html

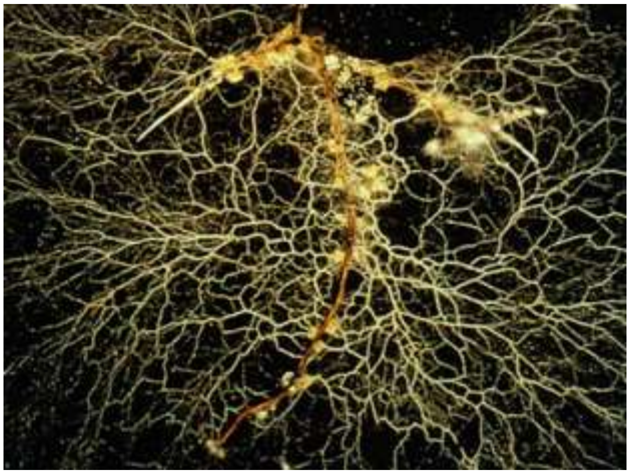

Figure 6: Picture of the increased root surface area of a plant due to the relationship with mycorrhizal fungi.
Credit: http://creating-a-new-earth.blogspot.co.za/2012_04_01_archive.html.

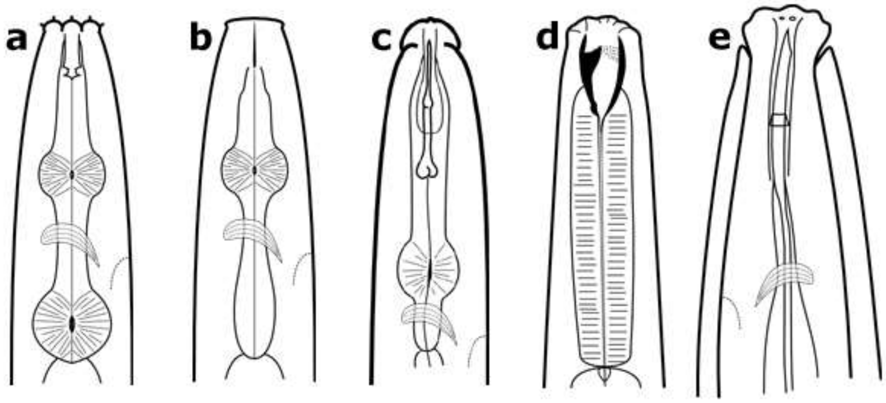

Figure 7: Nematodes are classified into different feeding groups based on the structure of their mouthparts. (a) bacteria feeder; (b) fungi feeder; (c) plant feeder; (d) predator; (e) omnivore. Credit: Ed Zaborski, University of Illinois.

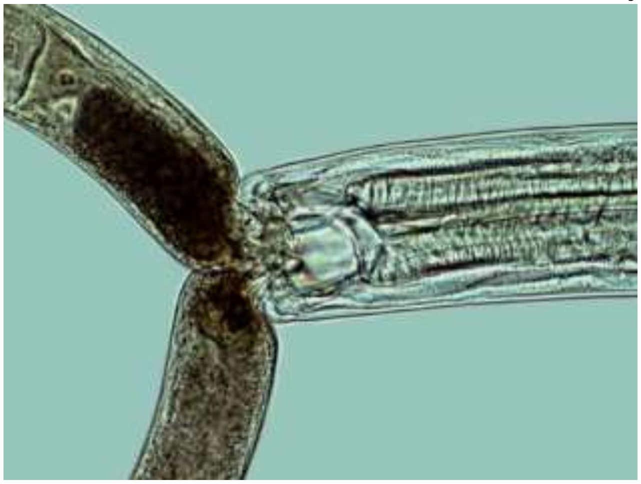

Figure 8: Light micrograph of a predator nematode feeding on another nematode. Credit: J.D. Eisenback