Concise overview of microbes related to soil health

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INTRODUCTION

Microbes are a fascinatinating subject, therefore the aim of this paper is to introduce readers unfamiliar with the topic, to microbiology. Microbial activities have a profound influence on soil health and for that matter on the world, as we recently experienced with the Coronavirus where the global economy slumped below the financial crisis of 2008.

The diversity of microbes in soil is stunning. A fifth of a teaspoon of topsoil contains between 10^8 (hundred million) to 10^9 (milliard) microbes, representing from ten thousand to a million different types of organisms. The main characteristic of a healthy soil is biodiversity, especially on the microbial level. The more diverse the biotic component of the soil, the more resilient the soil system is. Diverse communities may also be able to access varying resources more effectively because each species may have a different strategy for resource acquisition. A soil system is bound to face disturbances, e.g. drought, flooding, fluctuation in aeration or lack of nutrients. The more species the system has, the higher the likeliness that a species or several have the traits that allow them to adapt to a change. The more complex that these soil systems are, the more easily they can resist a stress. A dynamically stable system is one that is relatively immune to disturbances and is more likely to have more biotic interactions. These interactions are what stabilise a soil system. Another important factor in a stabilised environment is the variation of genes. Microbes evolve more rapidly than other organisms, creating phylogenetic diversity which assists these species' survival against negative changes in their environments or enable them to utilise new resources. In such a system biological productivity is sustained, and environmental quality, plant and animal health promoted.

Studies of agricultural stabiliy and sustainability range from the mega level to the minute. Soil ecologists have long recognised the importance of scale. Today enzyme reactions and clay investigations are done on the nanometre scale, microbial activities at the micron scale, and plant-process-pedon interactions at the metre scale, while the agricultural ecosystem research may encompass several kilometres.

Spatial relationships in soils

In order to make sound sense of the soil processes, soil scientists study it on multiple scales, from the molecular – nm, microbial – µm, meso-soil fauna, aggregates and roots – mm, the whole plant and the soil pedon in m, and field and landscape on the km scale.

On the mega level various processes occur (Fig. 1). Above ground is the living biomass where exchange of material and energy occur with other parts of the ecosystem; litter decompose, nutrients are released and eventually taken up; and inputs by humans are shown, such as fertilisation and irrigation.

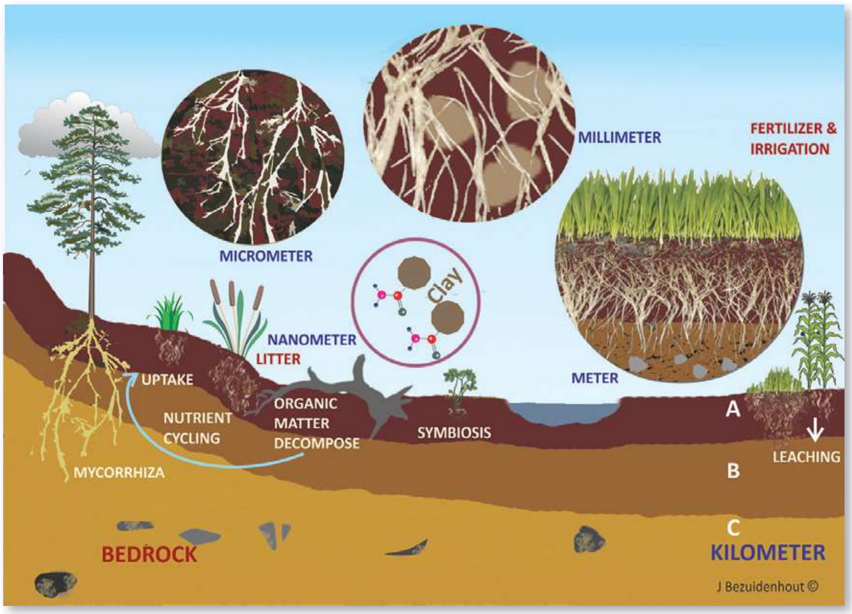

Figure 1: An ilustration of spacial relationships related to soil, ranging from the kilometre scale, metre, millimetre, micrometre to nanometre. On each level, scale different components and processes can be distinguished

When we zoom in on the m scale, we can recognise in the A-soil horizon root growth which can lead to weathering; Soil organic C is catalyzed by extracellular to Dissolved Organic Carbon (DOC). Bacteria use this as a C-source, releasing CO_2, which plants fix to organic compounds through photosynthesis. Nutrient cycles occur (Fig. 2).

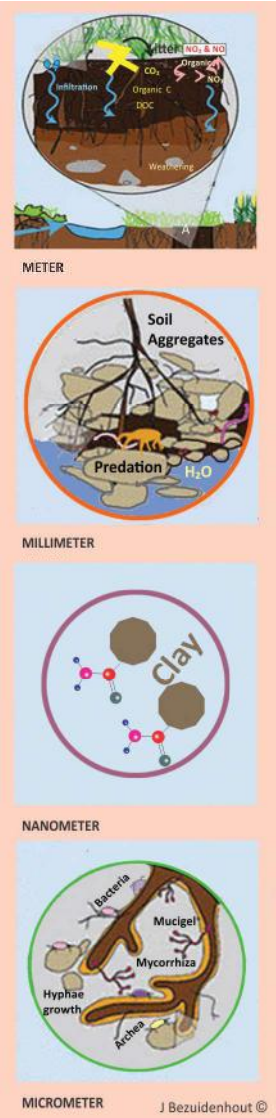

Figure 2: Components of soil visible with increased magnification

From the A-horizon, we zoom in a 1 000 times to reach the mm scale where you will notice nematodes, small bugs like mites of which some feed on nematodes, and then a crucial aspect of a healthy soil – aggregates.

From mm we zoom in a further 1 000 times bringing us to the millionth of a metre where we detect strange creatures. Fungi with a hyphal growth habit are covered with a gel called mucigel, there are mycorrhiza, which are a specialised group of fungi, bacteria and archea.

The smallest circle illustrates biochemical processes on the molecular level with individual bonds and atoms occurring at even smaller scale. Typically, enzymes are 3-4 nm in size, as are the micropores of minerals. Clay particles with lengths of 2 µm, but with an edge of 1 nm, have a surface area approaching 1 000 $m^2\ g^{-1}$. Although soil microbial organisms associated with the clay fractions are usually attached to the particles, particles can often be attached to the microbes as well.

Variety of soil microbes

The variety of soil microbes can be illustrated by their type of energy and carbon requirements and whether they need oxygen for their metabolic activities or not. Soil microorganisms differ in their energy and carbon requirements (Fig. 3).

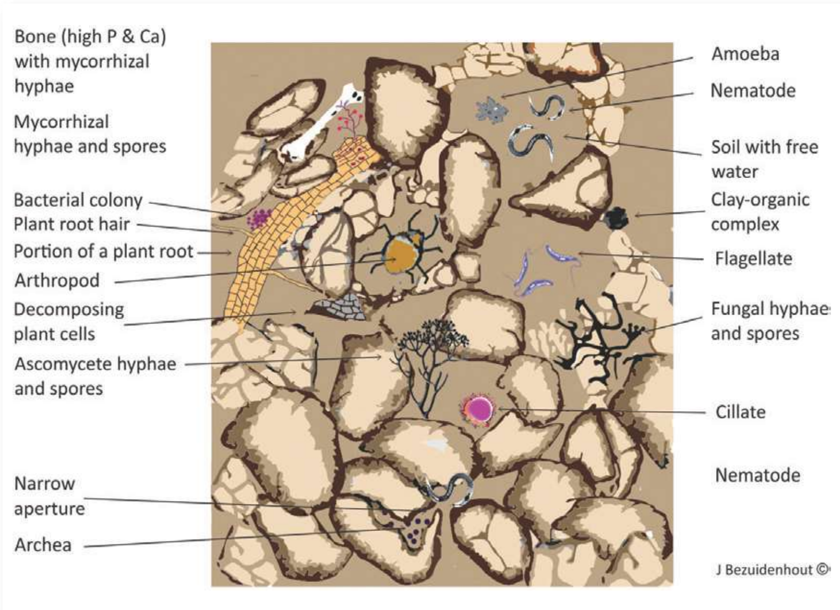

Figure 3: Classification of microbes according to the energy and carbon requirements

The first level of such a classification relates to the energy source of the microorganisms; phototrophs use light, and chemotrophs use chemical energy. The second level relates to the carbon source. Lithotrophs (*litho* = rock in Greek) use carbon dioxide (CO_2), whereas organotrophs use organic compounds. Cyanobacteria and green sulphur bacteria are examples of photolithotrophs, whereas the purple non-sulphur bacteria are photo-organotrophs. Sulphur- and iron-oxidizing bacteria and nitrifiers (which oxidize ammonia to nitrate) are examples of chemolitotrophs, whereas fungi are examples of chemo-organotrophs.

Although the physiological classification based on energy/carbon source enables us to make deductions as to their potential function, there are exceptions to this rule. For example, some bacterial nitrifiers have a range of complex physiologies that cannot always be classified according to Figure 3, because they change their physiological strategy depending on the type of energy source available.

Free oxygen is the third criterium to distinguish organisms. Soil microbes may either need oxygen (aerobes) or not (anaerobes) – for some anaerobes, oxygen may be actually toxic. The third group is microaerophiles which need oxygen but grow optimally in an environment with a very low concentration of oxygen. The fourth group can switch from aerobes to anaerobes, depending on the availability of free oxygen. An example is yeasts (type of fungi) which produce CO_2 under aerobic conditions and alcohol when the free oxygen is depleted.

Fungi

A few facts regarding fungi:

- They were instrumental for aquatic plants to colonise land by the ancestors of today's terrestrial plants.
- Fungi were involved with termination of C deposition into geological reserves, for example coal. The conditions that created coal began to develop about 300 million years ago, during the Carboniferous period. Fungal degradation of lignin via white rot arose in the same period; that was associated with the production of the first enzymes, degrading lignin and, along with geochemical factors, contributed to the decline of coal formation toward the end of the Permo-Carboniferous period.
- Fungi interact intimately with living and dead organisms, especially plants.
- They have profound influence on bio-geo- chemical cycles.
- Fungi are decomposers *par excellence*.
- Due to their growth habit, they can survive where bacteria and archea cannot.
- They form mycorrhizal symbiosis with roots which permitted plants to survive in challenging habita.

Bacteria and archea

During the 1990's taxonomists, using genetic tools, came to the conclusion that three life major forms of life exist – bacteria, archea and the eukaryotes. An eukaryote contains a nucleus with genetic material enclosed in a membrane, while bacteria and archea do not contain a true nucleus – that is the genetic material that is not enclosed by a membrane. The eukaryotes include fungi, plants and animals.

Bacteria and archea are sometimes lumped together as prokaryotes. Yet, although they look superficallly very much alike, the genetic difference between them is vastly larger than the difference between a plant and an animal.

Archea is often associated with extreme environments, such as seavents where some of them thrive at more than 100°C using hydrogen sulphide, the gas you smell with a bad egg, as energy source.

Less than 10% of the bacteria and archea can be cultivated, thus novel methods are employed to study their activities.

Morphology of microbes

The morphogy of microbes range from very simple to highly complex, the latter are the protozoa (amoebas, cillates and flagellates) – single cell eukaryotes or the higher fungi, such as ascomycetes illustrated in Figure 4.

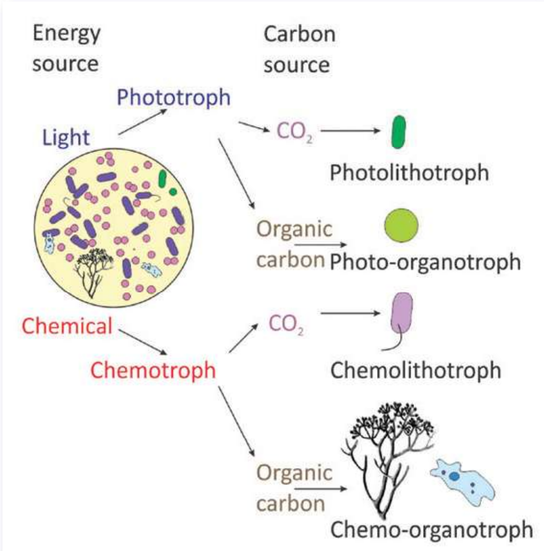

Figure 4: Diagramatic representation of a one centimetre soil slice

Soil aggregates

Soil aggregates, either as micro-aggregates (<250 µm) or macro-aggregates (0.25 to 2 mm) are self-organised from clays, carbonates and other mineral particles (Fig. 5). Nutrients bind with the aggregates thus limiting leaching. Bacteria and archea are mainly associatiated with micro-aggegates, while fungi and mycorrhiza are components of the macro-aggregates.

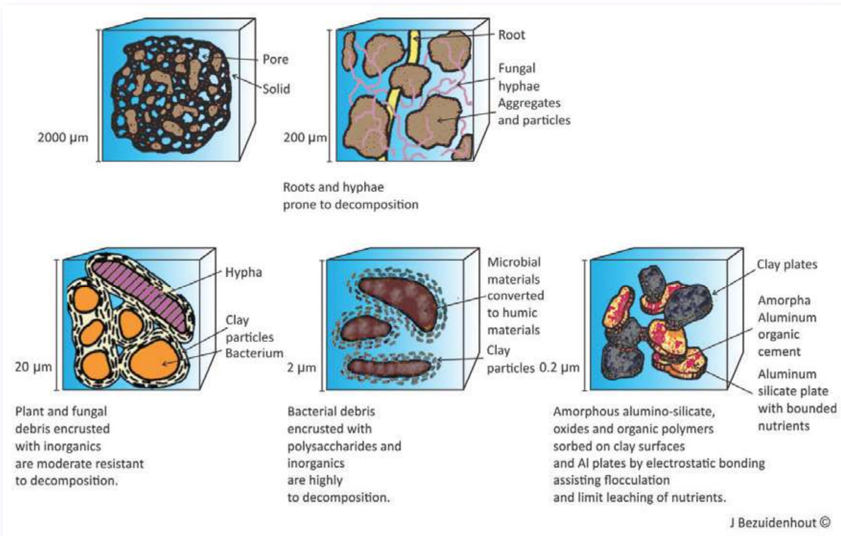

Figure 5: The hierarchial structure of soil

Micro-aggregates are especially resistant to mechanical breakdown, for example, from the impact of rainfall. The restricted size of the pores contained within these aggregates can limit accessibility of the associated

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colloidal humus to microbial decay and restrict physical interactions of soil organisms, thereby protecting microorganisms from predation by predators like nematodes or protozoa e.g. amoeba. Macro-aggregates usually remain intact as long as the soil is not disturbed, for example, by earthworm and termite activity, by the impact of intense rainfall, or by tillage.

The pore spaces contained within macro-aggregates, referred to as intra-aggregate pore space, are important for providing soil aeration and water retention for plant growth. The pore space surrounding macro-aggregates, collectively referred to as the interaggregate pore space, is where plant roots and larger fragments of plant residues are found.

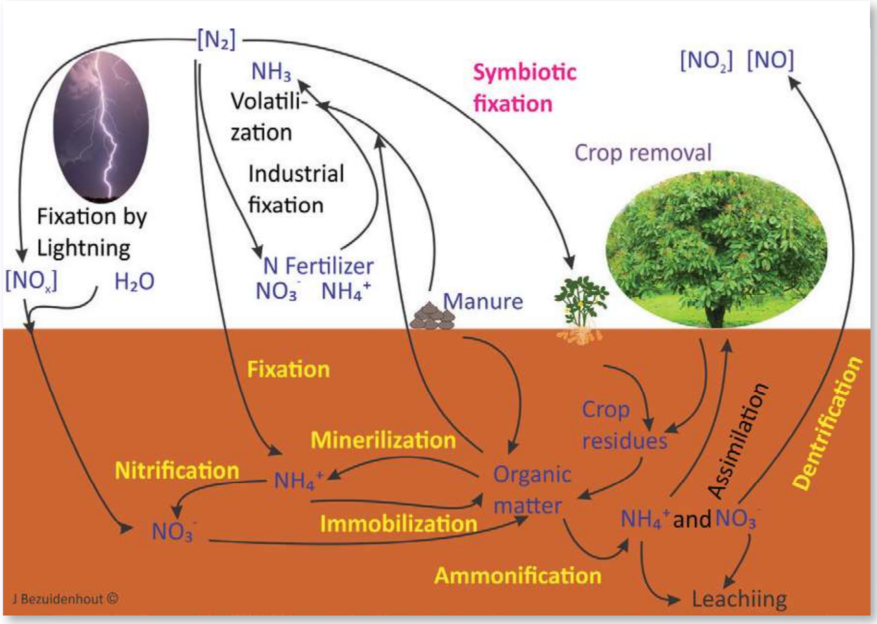

Figure 6: Schematic diagram of the transformations of elemental nitrogen and nitrogen compounds

Transformation of nitrogen and phosphorus

No other elements essential for life takes on as many forms in soil as nitrogen (N) and phosporus (P). The transformations of N compounds are mostly mediated by microbes and, to a lesser extent, of P-compounds. Soil microbiology thus plays a crucial role in ecosystem dynamics. In most terrestrial ecosystems, N or P limits plant growth, and thus production. The productive capacity of the system is therefore regulated by the rates at which soil microbes transform N and P to plant-usable forms.

Nitrogen

The enormous energy of lightning breaks nitrogen molecules and enables their atoms to combine with oxygen in the air, forming nitrogen oxides. These dissolve in rain, to form nitrate that are carried to the earth. Atmospheric nitrogen fixation contributes some 5-8% of the total nitrogen fixed (Fig. 6).

Beside abiotic nitrogen fixation, nitrogen fixing bacteria exist as well. Some live in a symbiotic relationship with plants of the legume family (e.g. soybeans, alfalfa). Some establish symbiotic relationships with animals, e.g. termites, while others live free in the soil.

Nitrogen-fixing cyanobacteria are essential to maintaining the fertility of semi-aquatic environments like rice paddies.

The nitrogen compounds undergo a number of changes – ammonification, nitrification and denitrification. In all, bacteria are involved.

Transformation of phophorus compounds

Microbes bring about a number of transformations of phosphorus (Fig. 7):

1. Altering the solubility of inorganic P-compounds.
2. Mineralisation of organic compounds with the release of inorganic phosphate.
3. Converting the inorganic P into cell components, an immobilisation process, similar to that occurring with N.
4. Bringing about an oxidation or reduction of inorganic P-compounds.

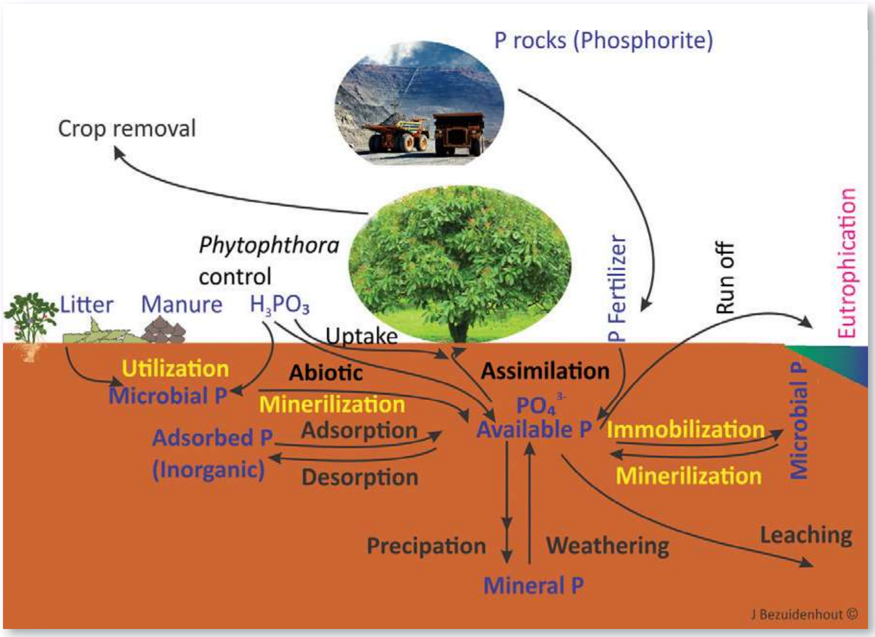

Figure 7: Schematic diagram of the transformations of phosphorus compounds

Particularly important to P cycle are the microbial mineralisation and immobilisation reactions. Biological oxidation of phosphorous compounds occurs. Phosphite (HPO_{2-}) is oxidized to phosphate. A number of heterotrophic bacteria and fungi utilise phosphite as sole P source.

Hypophosphites (HPO_{2-}) can also be oxidised to phosphate by heterotrophs:

$$HPO_{2-} \longrightarrow HPO_{2-}$$

Besides oxidation, bacteria can reduce PO_{3-} to phosphite and hypophosphite:

$$H_3PO_4 \longrightarrow H_3PO_3 \longrightarrow H_3PO_2$$

Thus phosphorus alternates between organic and inorganic, and soluble and insoluble forms. Insoluble P is solubilised by various acids produced by microbes.

Concluding remarks

Most avocado farmers limit the manipulation of microbes by controlling fungal pathogens and improve soil biodiversity and soil structure by mulching. Yet many other opportunities exist to improve the physical, chemical and biological characteristics of the soil. Some examples are to inhibit activity of denitrifiers, enhance mycorrhizal growth, and consider the use of symbiotic nitrogen fixing plants.

Many of the agricultural practices we use today actually cause deleterious effects on microorganisms and their processes. Plowing and clear-cutting forests, decrease organism populations and promote nutrient loss with an overall decrease of soil quality.

The author trusts that with this concise overview, readers may explore possibilities to improve soil health, increase soil biodiversity and enhance soil ecosystem stability.

Recommended reading

PAUL ELDOR, A. (editor). 2015. Soil Microbiology, Ecology, and Biochemistry. Elsevier, Amsterdam.