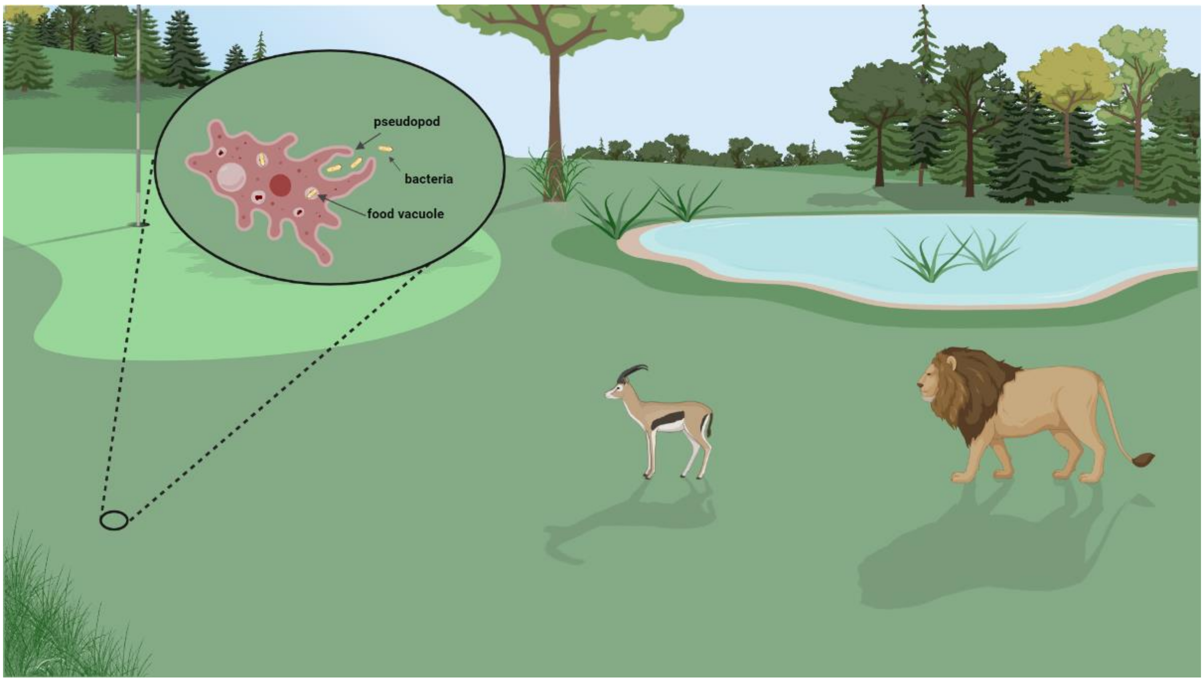
Microbial Predator-Prey Interactions in Soil

Mommy: Lions hunt gazelles; who hunts the microbes?



Small and large predator-prey relationships: amoebae–bacteria and lion-gazelle as predators and preys.

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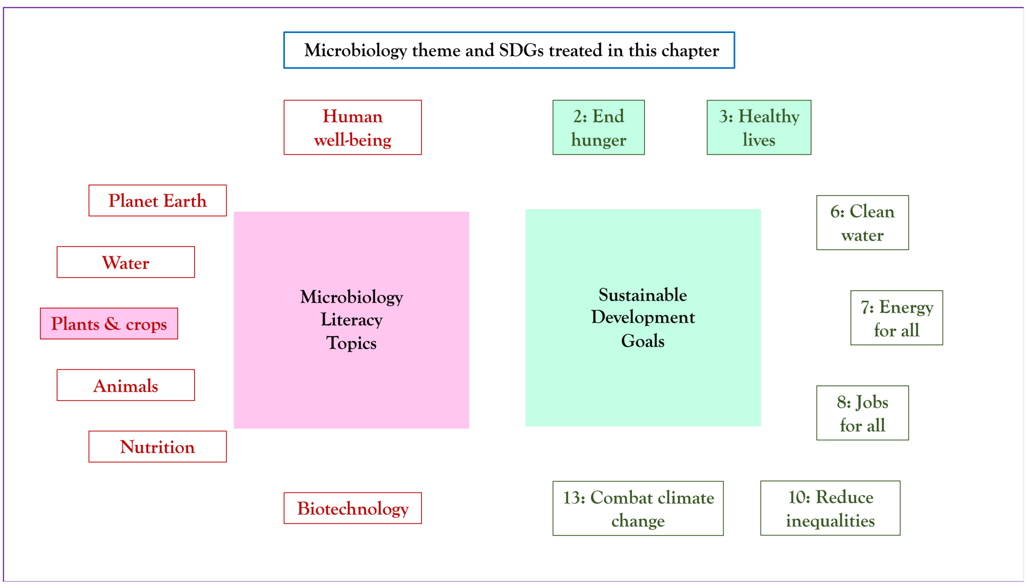
Storyline

We all know about predator–prey relationships in nature, be it cats chasing and eating mice or lions hunting for gazelles. These interactions naturally regulate the sizes of populations. That is: when lots of gazelles exist, it is easier for lions to kill them and then the gazelle population does not grow too much. On the other hand, if there are only a few gazelles and many lions, the lions will not have enough food to prey on and hence their population will not grow. As a consequence, the predators and the prey keep each other in check. This is a common phenomenon in nature allowing different animals and other organisms to make sure that none of them take over entire stretches of land.

One can observe these predator–prey interactions on different scales. Huge organisms such as whales may prey on tiny organisms such as plankton. And tiny birds will prey on even tinier worms. There are also almost invisibly small predators that prey on even tinier creatures. These are microorganisms. As the name suggests, the key players are microscopically small – so small that you need an apparatus that magnifies them until you can observe them: a microscope. Some organisms, called amoebae, are an example of these tiny predators. They are really small: when you align a hundred of them, this line will be around one millimetre in length. These amoebae eat bacteria. You may have heard of bacteria as they can cause diseases. Many of them, however, just live in the soil, in the water, on the cover of your smartphone, or on your skin without causing any harm. As we will see, many bacteria are really important and good for the well-being of our environment. A lot of these bacteria are delicious for amoebae and they constitute their food source. When an amoeba encounters a bacterium, it literally engulfs it for digestion.

Within the soil, these amoebae will prey on bacteria and – similarly to the gazelles and the lions – these organisms regulate the size of their populations. As such they ensure that certain bacteria do not take over entire parts of the soil. This is important to keep a healthy mixture of microbial organisms in the soil. If in balance, they contribute to a healthy soil that can be used to grow crops.

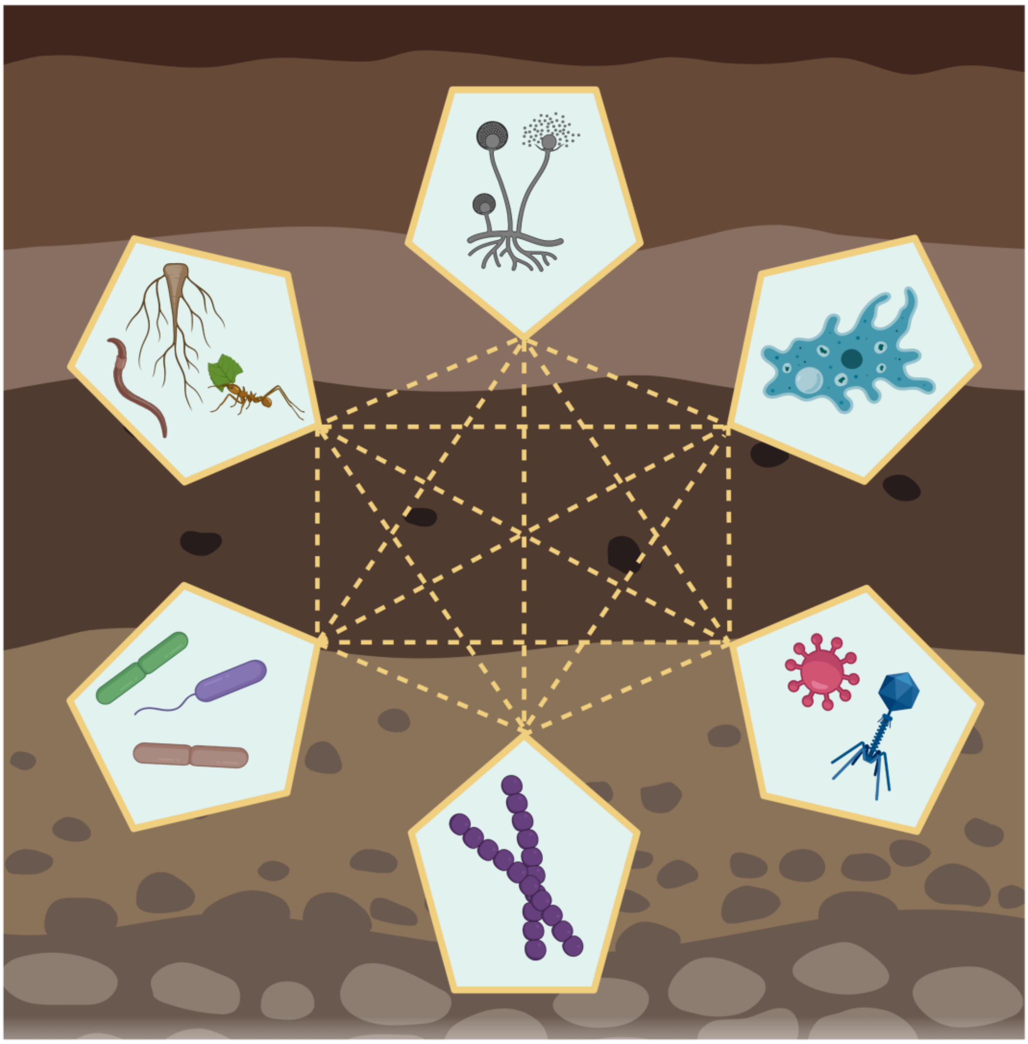
The Microbiology and Societal Context



The microbiology: microbial predation shapes the microbiome structures, showing plant-beneficial functional traits by providing the services required to improve plant growth and health. Bacteria defend against predators mainly by secreting natural products that can be widely used to develop new medicines for humans and crops. *Sustainability issues:* ecological balance, nutrient cycling, medicines, health, and food.

Microbial Predator-Prey Relationships in Soil: The Microbiology

1. The Invisible Life in Soil



Various soil-dwelling organisms (from top clockwise: fungi, amoebae, viruses, actinobacteria, rod-shaped bacteria, and plants with small animals)

2. ***Soil Composition.*** Soil is virtually everywhere – but what is it actually? It is a material composed of five ingredients: minerals, organic matter, living organisms, gas, and water. This is not an independent mix, but rather a living and dynamic system with a particular size, form, and history. Just like a body of water may contain fish, algae, and crabs, a body of soil is an entire system containing rocks, roots, animals, and other parts. And like other bodies, soil systems fulfil diverse functions that – together – are greater than the sum of their parts.

1. **Regulation of Above-Ground diversity**
2. **Decomposition and Nutrient cycling**
3. **Sustaining marine life**
4. **Agriculture and cultural heritage**
5. **Development and Bioremediation**
6. **Climate regulation and Carbon storage**

3. ***Soil Functions.*** All components of the soil interact with each other and their surrounding environment. Thereby, they provide a multitude of benefits to the world and as a consequence to our society. Some main functions and benefits of soil are:

a. Decomposition. When organisms die, bugs, fungi, and other creatures work together to break down the dead organic matter to recycle it. This "cycle of life" or "decomposer food web" generates nutrient-rich soil. Microbes which decompose organic matter enable new living organisms to grow and even enhance the growth of plants. If these processes are in balance, the stable and undisturbed soils – also known as ecosystems – can thrive for long periods of time.

b. Nutrient Cycling. In the process of nutrient cycling, nutrients of minerals from rock and dead biomass are converted into simple compounds that can be taken up by plants and other organisms. All soil organisms contribute to nutrient cycling through a number of physical and chemical processes. As an example of a physical process, imagine pieces of leaves being broken down into smaller parts as we and other animals step on them. This occurs also on tinier levels, as bugs break down the leaf parts which are then pulverized by even tinier microbes. Chemical processes also play an important role: certain reactions facilitate the transformation of organic matter into minerals. Plants can then take up minerals and nutrients which stimulate their growth. In turn, this leads to more plant material being added to the soil, like fruits or leaves, which can be used by other organisms.

c. Regulation of Above-Ground Biodiversity. Communities below-ground influence the activities above-ground, such as plant growth. This influence can be exerted directly, for example by symbionts, which help host plants take up nutrients via their roots. The influence can also be exerted indirectly via the activity of the decomposer food web (explained above) which regulates nutrient availability to plants. In this way, interactions between above- and below-ground communities drive plant biodiversity and the dynamics of whole ecosystems.

d. Climate Regulation. Regulating the global climate is an important ecosystem function that soils perform by storing carbon (C) and minimizing greenhouse gas emissions, such as nitrous oxide (N_2O). Increasing organic carbon in soil can be achieved in agriculture through practices like:

i. adding organic fertilizers to crop fields
ii. incorporating crop residues in the soil after harvest
iii. cultivating cover crops – plants that are seeded to cover the soil rather than to be harvested

In addition to storing carbon, preventing its emissions leads to less carbon in the atmosphere. Practices for reducing carbon emissions include:

i. eliminating fossil fuels as an energy source
ii. reducing tilling and ploughing of soil for agricultural crops, which keeps more organic matter in the soil, leads to better nutrient cycling, and protects the soil from erosion, i.e. removal of soil material by wind, water and other natural forces

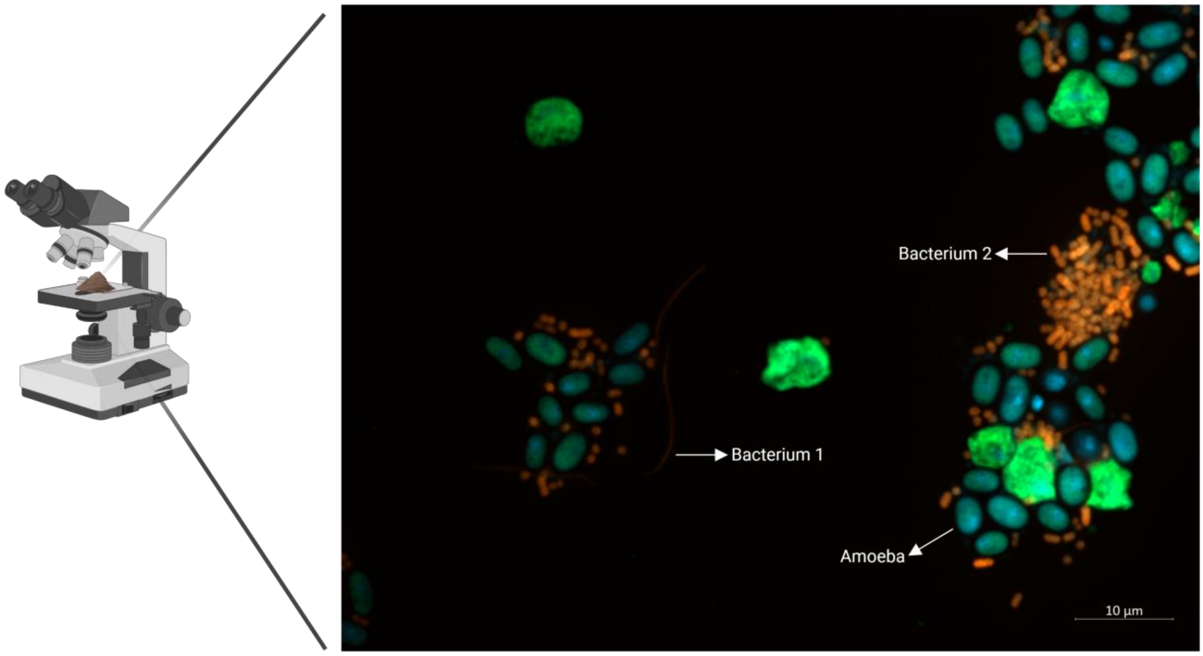
e. Bioremediation. Soil microbes like bacteria and amoebae break down pesticides and other contaminants, and kill harmful bacteria. This is important for the soil ecosystem because these contaminants would otherwise increase or accumulate and be harmful for other microbes, animals, and plants in the soil. It is also important for us because water that seeps through the soil can enter groundwater reservoirs. As it filters through the soil, it is cleaned by microbes and minerals, thereby enabling us to safely use these reservoirs as drinking water supplies.

All these important functions are carried out by tiny organisms in the soil. We can understand some of this activity by directly observing what is going on when for example small beetles decompose plant material. However, most of the microbial activity happens on such a small scale that it seems invisible to our eyes. By using sophisticated tools, we can nevertheless reveal even the hidden lives of microbes.

4. ***A Gateway into the Microverse.*** How can we understand something that we cannot see? In the past, the lack of this knowledge made people believe that harmful gases or evil spirits were the cause of illnesses. But we slowly began to understand the relevance of the microscopic world once we were able to see its members.

Our eyes help us see the macroscopic world around us. But what about the microscopic world? These tiny beings play a key role in shaping various ecosystems and are also involved in the development of the human community. Sadly, our eyes are ill-equipped to see the wide variety of microbial interactions happening right under our noses. There is no fun if we are unable to see them. The smallest object we could see is the width of the human hair (0.04 mm) which is just the tip of the iceberg. To see anything smaller than that, we need aid by some special tools.

This is where microscopes come into the picture. A microscope is a device that can magnify small objects to make them appear larger so that our eyes can see them. Since their invention in the 16th century, more than 400 years ago, microscopes have undergone several changes to allow us to see the intriguing life of microbes. Nowadays, microscopes are powerful enough to examine the anatomy of these microorganisms. But microscopy (that is the use of microscopes) is not just restricted to biology. Even chemists and materials scientists use complex microscopes to understand the structures of various molecules and surfaces. So researchers, who are seeking knowledge of the natural and the physical world, use microscopes for their work. Therefore, microscopy has become an integral part of almost all aspects in research.



How microscopy and staining can differentiate various members of the microverse.

Sometimes, just seeing the microbial life is not enough. We have to identify them to understand their interactions. Therefore, along with the power of microscopes, several dyes and staining methods are used to create stunning images of microbial life. Like individual cars are painted differently, these dying techniques are also applied to identify the various microbial life forms. For example, staining helps us differentiate harmful microbes from useful ones and provide information on how they affect an ecosystem. In some cases, these methods also allow us to see microbes that cannot live outside their specific niche.

For complex ecosystems such as soil, the easiest way to understand its microscopic inhabitants is through imaging them with microscopes. We can also see how macroscopic life (that is bigger life forms which we can see by naked eye), like a plant root, interacts with its tiny counterparts like bacteria and fungi. Understanding this diversity in soil and its health is one of the areas where microscopy plays an important role.

These days, microscopy is not just confined to laboratories or scientists. Students and the general public can buy DIY microscopes to explore the microverse and understand the variety of life on Earth. Such innovations contribute towards better accessibility for public outreach programs and make you and the whole society aware of scientific research and conservation.

5. *Microbial Predator-Prey Interactions in Soil.*

Did you know that…

- the war between amoebae (predator) and bacteria (prey) happens every day in soil, just like lions hunting for gazelles on the grassland?
- the shape of amoebae is quite different from bacteria, which makes it easier to eat bacteria?
- different bacteria can team up to defend themselves against their predator?
- plants and crops can benefit from these amoebae-bacteria interactions?

Now, let us explore the predator–prey relationships in the microscopic world. Unlike bacteria, which have a stable shape, shell-free amoebae look like blobs. Movement of amoebae relies on the bulging parts called pseudopodia or “false feet”, which are extensions of the cell’s membrane. Amoebae can reach out and grab some surface with a pseudopod, using it to crawl forward. These “false feet” also help amoebae to eat. A stretched-out pseudopod can cover and then swallow bacterial and fungal cells, even some small worms.

However, bacteria also have a range of defence strategies to prevent this predation. When an amoeba is close to bacteria, the bacteria may change their size and shape to prevent the amoeba from swallowing them. They can also increase motility (that is their ability to move) to escape the predator. Sometimes, they produce compounds that kill amoebae, so-called amoebicidal compounds. And, even more interestingly, a particular bacterium may cooperate with another one. By working together, they can protect themselves by teaming up to produce an amoebicidal compound.

These predator–prey interactions in soil play an essential role in plant nutrition. Plants need things like carbon and nitrogen to grow. The carbon part is no problem: they can use carbon dioxide (CO_2) from the air in the process called photosynthesis. However, the nitrogen has to come from the soil. Luckily, amoebae need more carbon than nitrogen, so when they are consuming bacteria or fungi, excess nitrogen is released as waste into the soil, which can be used by plants.

6. The Potential of Soil Biodiversity. Predator–prey interactions are important factors for evolution. As it can be observed in the animal kingdom there are several ways to avoid threats of predation. Elephants or rhinos for example grow tall so that they do not need to fear any natural feeding threats. Other animals like gazelles are so fast that they may escape their predators due to their high speed.

But these strategies – bigger, faster, stronger – are not usually applicable to microorganisms, because being small has its own advantages. So microbes have developed alternative ways to survive. As we learned above, there are various threats and burdens for microorganisms to overcome. Their strategies often include the production of natural products – substances not playing a role in growth or reproduction, but having other important biological activities. On one hand, these compounds can act as chemical “armor”, which protects the host organism like a special coating. On the other, there are compounds which can actively interact with the predator and kill it, or at least inhibit it or fend it off. By researching and understanding these kinds of competition, and the chemical warfare involved, we can even gain something that may be very useful for us humans. Compounds which were initially produced to provide competitive advantages for the microbes are now used by scientists to improve human health and well-being.

a. In medicine. There are plenty examples of natural or nature-inspired drugs, which are used to fight infections or many other diseases. For example, antibiotics such as vancomycin or nystatin are used to cure bacterial or fungal infections. Many of these drugs were discovered by studying microbial interactions.

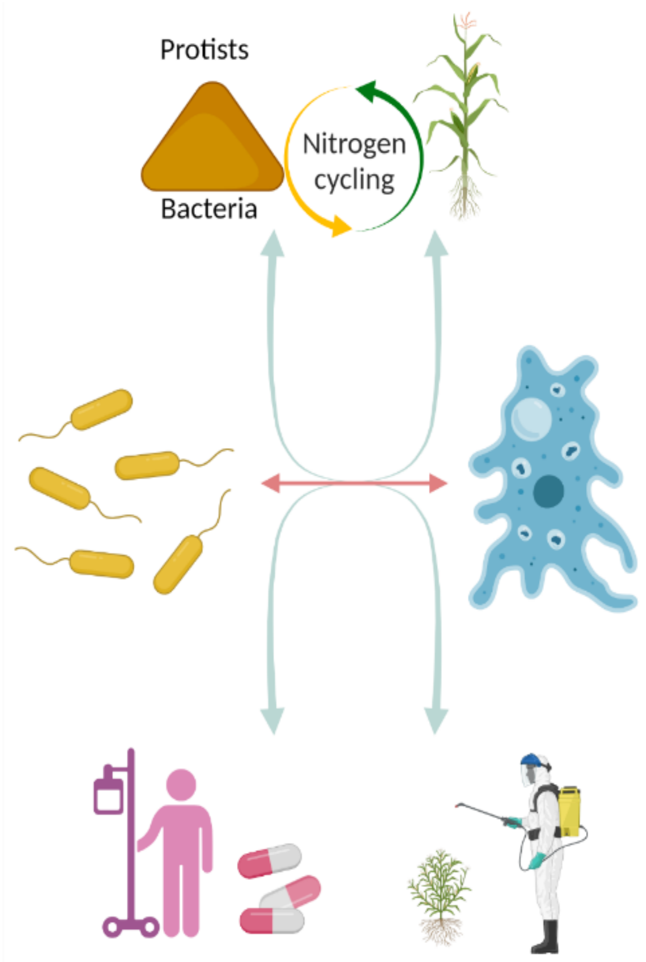
b. In agriculture. Another important field in which microorganisms play a crucial role is agriculture. Since the overall human population is steadily increasing, the demand for food is increasing as a consequence. Unfortunately, space – especially for agriculture – is limited on this planet and therefore it is necessary to increase the yield of crops. Crop yields are affected by a number of different factors, such as weeds, which compete for space, light and nutrients, climate such as drought and temperature extremes, pests which eat or cause disease of plants, and so on.

Beside breeding plants to be more resistant to extreme environmental conditions, it is possible to use chemical compounds. There are many products – agrochemicals, such as glyphosate – which either reduce the number of unwanted weeds or protect crop plants from parasites. The problems are that compounds designed to kill certain organisms, such as insect pests, may (a) kill or at least negatively affect other organisms, such as pollinators like bees, and (b) when applied repeatedly to crops need to be efficiently degraded by microbes, to prevent their accumulation in the environment. However, some of these compounds are difficult to degrade by microorganisms, so indeed accumulate in the soil, in the groundwater, and even in the food produce. For many of these compounds, there is little knowledge about how they affect the environment and humans on the long term. Even worse, as more and more chemicals accumulate in the environment, we are faced with complex chemical mixtures whose effects are totally unknown and extremely difficult to assess.

An alternative strategy, and a means to bypass these problems, is the use of biocontrol agents – organisms that inhibit the growth and/or reproduction of other organisms. This means introducing special microorganisms – biopesticides – with their chemical arsenal into the soil to provide benefits similar to those achieved by agrochemical pesticides. Although we do not yet know about the wider effects of the natural compounds in predator-prey relationships, it is more likely that they have evolved to be rather specific so should be less harmful in terms of unintended side effects. Another aspect is that many natural products are only produced when they are needed. This targeted production of chemical compounds can significantly reduce the overall amount of agrochemicals introduced into the environment, and therefore contribute to soil and crop protection.

As mentioned above, there is an increasing demand for agricultural products for food supply and biofuel production. Recent studies regarding the influence of different farming systems on the soil microbial community revealed a negative influence of conventional farming towards the micro-biodiversity. In these studies, the effect of fertilizers and agrochemicals was compared to organic farming systems. The overall results indicated a reduced microbial heterogeneity in conventional farming systems. It is assumed that the use of synthetic compounds as well as long term monocultures lead to a loss of ecological niches. As a consequence of that, the habitat for microbes specialized to these niches is limited and therefore reduces the overall heterogeneity of the soil microbiome. The long-term effects of this biotic homogenization is not well understood and therefore it is not yet possible to comment on the consequences.

In summary, we can appreciate that microbes are important organisms in the soil. Even if we cannot easily see them, they can be hunted by small predators. But these tiny prey can fight back. This microscopic form of warfare can be responsible, eventually, for a healthy environment and, if we understand how the warriors use their arms, we can even repurpose these defence mechanisms to cure diseases.



Natural products from predator–prey interactions can be used for medicine and agriculture.

Relevance for Sustainable Development Goals and Grand Challenges

- **Goal 2. End hunger and malnutrition, increase agricultural productivity.** The consumption of soil bacteria by amoebae increases the turnover of nutrients. The reason for this is that amoebae have a higher C:N ratio than the bacteria or fungi they consume. As a result, they excrete excess N, making it available to the host plant, which in turn increase agricultural productivity.
- **Goal 3. Ensure healthy lives and promote well-being for all at all ages.** In addition to contributing to agriculture, microbial communications will also benefit human health even more. There are many examples of natural or nature-inspired medicines which are used to fight infections or many other diseases. For example, antibiotics such as vancomycin or cystine are used to treat bacterial or fungal infections. Many of these drugs were discovered by studying the interactions of microorganisms.

The Evidence Base, Further Reading and Teaching Aids

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Glossary

- **abiotic:** anything relating to or resulting from the absence of living organisms
- **agrochemical:** any chemical used in agriculture, including chemical fertilizers and pesticides such as herbicides and insecticides
- **amoeba:** single-celled animal that catches food and moves about by extending finger-like projections of protoplasm, called pseudopodia
- **bacterium:** one-celled organism that lacks a cell nucleus and reproduces by fission or by forming spores. Some bacteria are important symbionts for animals or plants, others can cause disease.
- **biofuel:** any fuel that is derived from biomass (i.e. plant or algae material or animal waste). Since this material can be replenished easily, biofuel is considered to be a source of renewable energy, unlike fossil fuels such as petroleum, coal, and natural gas.
- **biotic:** anything relating to or resulting from living organisms
- **biodiversity** (also called **biological diversity**): the variety of life found in a place (e.g. all different kinds of animals, plants, fungi, or microorganisms like bacteria in a specific part of soil)
- **biopesticide:** biological substance or organism that damages, kills, or repels organisms seen as pests (e.g. naturally occurring substances, microorganisms, or pesticidal substances produced by plants containing added genetic material)
- **breeding:** changing the traits of organisms such as plants or animals in order to produce desired characteristics
- **conservation:** careful preservation and protection of something, e.g. natural resources for current and future generations
- **DIY:** do-it-yourself, i.e. done or made without paying someone else to do it
- **ecological niche:** match of a species to a specific environmental condition, including biotic and abiotic factors affecting it
- **ecosystem:** the complex of living organisms, their physical environment, and all their interrelationships in a particular unit of space
- **fungi:** any member of taxonomic kingdom Fungi. Fungi lack chlorophyll, leaves, true stems, and roots, reproduce by spores, and live as saprotrophs or parasites. The group includes moulds, mildews, rusts, yeasts, and mushrooms
- **heterogeneity:** the state or quality of consisting of parts or things that are different, distinguishable from each other
- **homogenization:** the process of changing something so that all its parts or features become the same or very similar

- **macroscopic:** the property of objects or phenomena to be large enough to be visible with the naked eye, without magnifying optical instruments. It is the opposite of microscopic
- **microbiome:** community of microorganisms that can usually be found living together in any given habitat
- **microscopic:** so small as to be invisible or indistinct without the use of the microscope. It is the opposite of macroscopic
- **microverse:** short for "microbial universe", i.e. the perception and experience of particular characteristics on the microbial scale
- **monoculture:** the practice of growing one crop species in a field at a time. Monoculture crops have allowed farmers to increase efficiency in planting, managing, and harvesting, mainly by facilitating the use of machinery in these operations, but monocultures can also increase the risk of diseases or pest outbreaks
- **natural product:** a natural compound or substance produced by a living organism, e.g. by cells found in nature or by isolated cellular components
- **sustainability:** ability to maintain or support a process continuously over time