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Soil Microbiomes and One Health

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Abstract

The concept of one health highlights that human health is not isolated but connected to the health of animals, plants and environments.

This review demonstrates that soils are a cornerstone of one health and serve as a source and reservoir of pathogens, beneficial microorganisms and the overall microbial diversity in a wide range of organisms and ecosystems.

Introduction

- A wealth of studies now demonstrate that microbial communities associated with plants, animals and humans function as a ‘second genome’, and thus drive the fitness and performance of almost all organisms on Earth.
- A growing number of studies also suggests that microbial communities of different organisms are interconnected and form a circular loop.
- However, compared with plant, animal and human health, the importance of the soil microbiome and soil health has received less attention among one health researchers until now
- The study assesses how soils can be the source of microorganisms for other ecosystems and identify microbial taxa that are shared between the different one health components
- The study will evaluate factors that regulate soil microbial contributions to one health and analyze these contributions in the light of environmental perturbations and dysbiosis and discuss how soil microbiomes can respond to such changes

Soil as source of microbiomes

Global carbon-biomass on Earth:

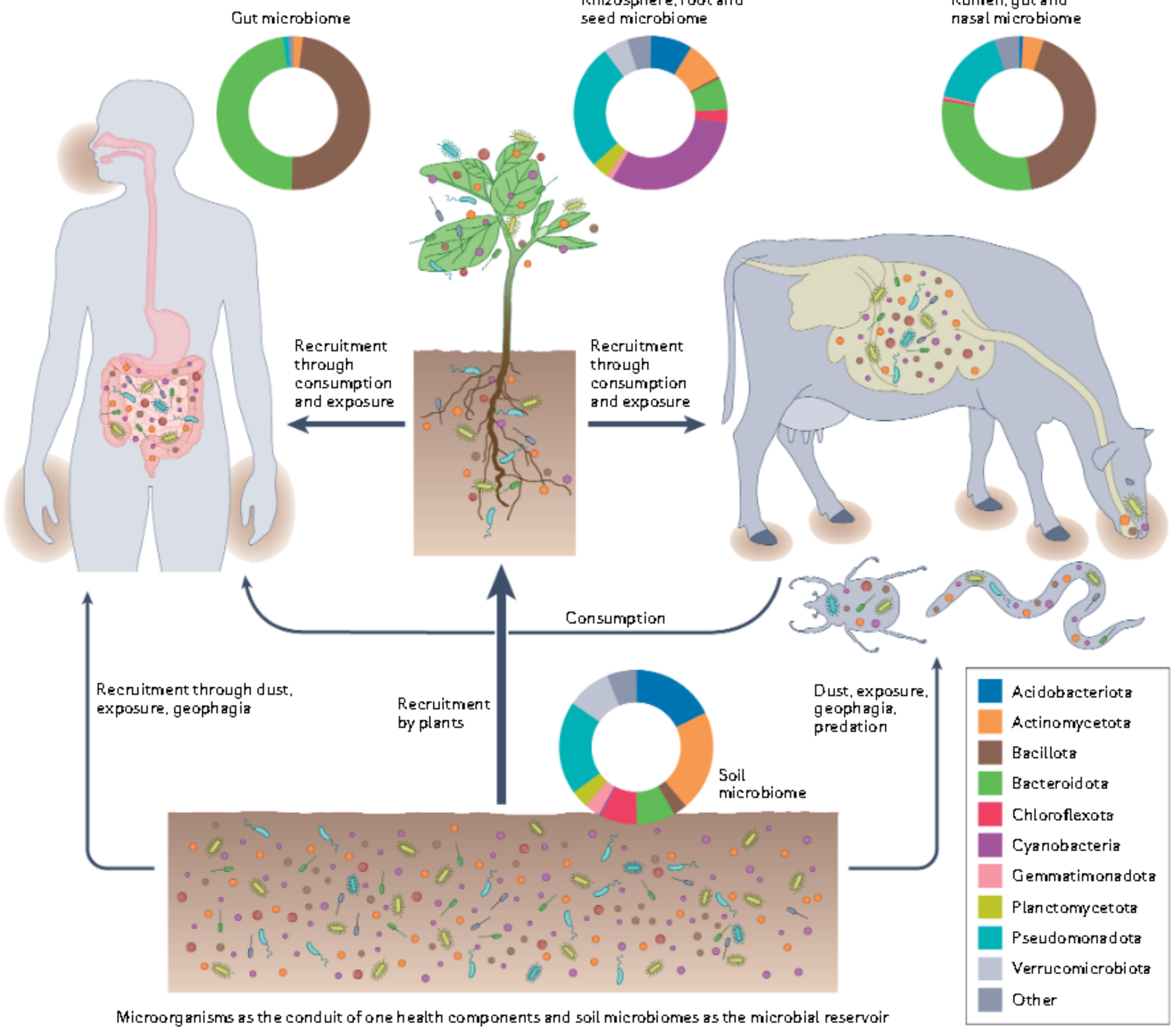
- 0,3% Animals
- 1% Archea
- 2% Fungi
- 15% Bacteria

- Soils harbour the most diverse and complex microbiome on Earth. One gram of soil has often more than 0.5mg of microbial biomass carbon and >50,000 species.
- Consider soil as a major source of microorganisms in terrestrial ecosystems and, thus, the foundation of one health

- The dominant players of each microbiome compartment (soil, plant, animal, human) vary considerably however humans and animals have shared microbiology with soil.
- Specialized members of soil microbial communities assemble in the **plant rhizosphere** and get preferentially recruited into the roots, and, as a result, plants receive a subset of the soil microbiome
- Bulk soil is the most important contributor to **plant endo-phytic microbiota**, contributing more than two- thirds of the bacterial and fungal diversity
- Geophagy, a deliberate consumption of soil or clay, is common among animals and humans
- Grazing sheep - up to 400g of soil/kg of body weight. Dairy cows - up to 350kg of soil/ cow/ year.

- Estimates suggest that up to 3% of the rumen microbiome of sheep and cattle can be contributed by the ingested soil.
- Soil-dwelling mice can directly acquire microorganisms from the soil that can alleviate inflammation and allergic diseases
- The skin microbiome composition of farm animals is also linked to the soil microbiome
- Different bacterial species are connected with high performance in poultry farms
- In cattle farms, soils can also be a recipient of antibiotic-resistance genes from the rumen microbiome
- Human geophagy has been reported in many parts of the world including Asia, sub-Saharan Africa, Latin America and the Pacific Islands
- Soil types (for example, clay loam soil versus loam soil) are correlated with the nasal and oral human microbiomes
- Higher soil microbial diversity, which has been linked to reduced risk of hospitalization for infectious and parasitic diseases in Australia
- The oral, nasal and skin microbiomes of farmworkers are associated with the soil microbiome composition of their farms.

Fig1. The link between soil, plant, animal and human microbiomes



Microorganisms as the conduit of one health components and soil microbiomes as the microbial reservoir

Soil microbial contributions to one health

Soil Health:

- Definition: the capacity of soil to function as a vital living system, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health
- The degradation of soils owing to land-use change, erosion, compaction and pesticide contamination has highlighted the urgent need for sustaining the **ecosystem services of soils**. Leading to a growing interest in the practices that can maintain healthy soils

- Crop diversification and reductions of synthetic pesticides, mineral fertilisers, and intensive tillage, can improve soil biodiversity and soil health
- Soil microbial communities can have direct and indirect influences on a multitude of processes, including nutrient cycling, organic matter dynamics, soil structure, carbon transformations and sequestration
- Microbial biomass, complexity and the presence of key microbial groups are associated with the stable pool of soil carbon, making microbial parameters essential for our predictive understanding of **soil carbon sequestration**
- However, whereas the physical and chemical indicators of soil health have been emphasised in the literature, the soil biological indicators have received little recognition

Plant Health

- Out of the approximately 29 essential elements for plants, 18 are obtained from the soil, and soil microbial communities play a central role in delivering these elements to plants (C, H, O, N, P, K, Ca, Mg, S, Fe, B, Cu, Cl, Mn, Mo, Co, Ni, Zn).
- The **rhizosphere microbiome** strengthens the metabolic repertoire of plants and facilitates a range of processes, including seed germination, seedling establishment, nutrition, water uptake, growth promotion, pathogen suppression, stress tolerance and hormone regulation
- Indirectly as well, microorganisms in the rhizosphere can influence important functional traits including leaf area, leaf longevity, leaf nutrient levels and the shoot to root ratio
- Soil microorganisms can shape the structure, composition and functioning of plant-associated microbiota.
- Microorganisms acquire up to 80% of plant nitrogen and 90% of plant phosphorus

- One of the most well-known examples of plant-beneficial microorganisms are the **mycorrhizal fungi**, which form symbiotic associations with nearly 90% of land plants, including many crops
- Plants obtain water and essential micronutrients and macronutrients from mycorrhizal fungi and supply up to one-quarter of their photosynthates in return
- Mycorrhizal fungi can enhance the growth of a wide range of crops by up to 50%
- Not all soil microorganisms promote plant health, and there are numerous soil-borne plant pathogens
- **Disease-suppressive soils** are soils that, owing to their microbiome composition and activities, prohibit pathogens from establishing or greatly reduce pathogen damage

Animal and insect health

- The soil environment can be a source of animal microbiomes, and microorganisms that animals ingest through food

- Studies show that insects acquire these microorganisms vertically (offspring) and also by feeding on plants and being exposed to microorganisms originating from soil.
- Soil microbiomes can even influence the health and **social behaviour** of soil-dwelling macroorganisms. For example, a recent study found that the abundance of the butyrate-producing bacterium *Kineothrix alysoides* in soil microbiomes was correlated to reduced anxiety in mice exposed through dust.
- Insects can also acquire soil microorganisms that depolymerize insecticides, making themselves insecticide-resistant
- A diverse soil microbiome can have positive implications for the **gut health and mental health of soil-dwelling mammals**
- Animal diseases can also directly develop from pathogen sources in soil and some of these pathogens can also directly or indirectly (as a zoonotic disease) infect humans
- Reserach is still unclear about which fraction of soil microbiota ends up in herbivores or carnivores, and how it affects the health of animals.

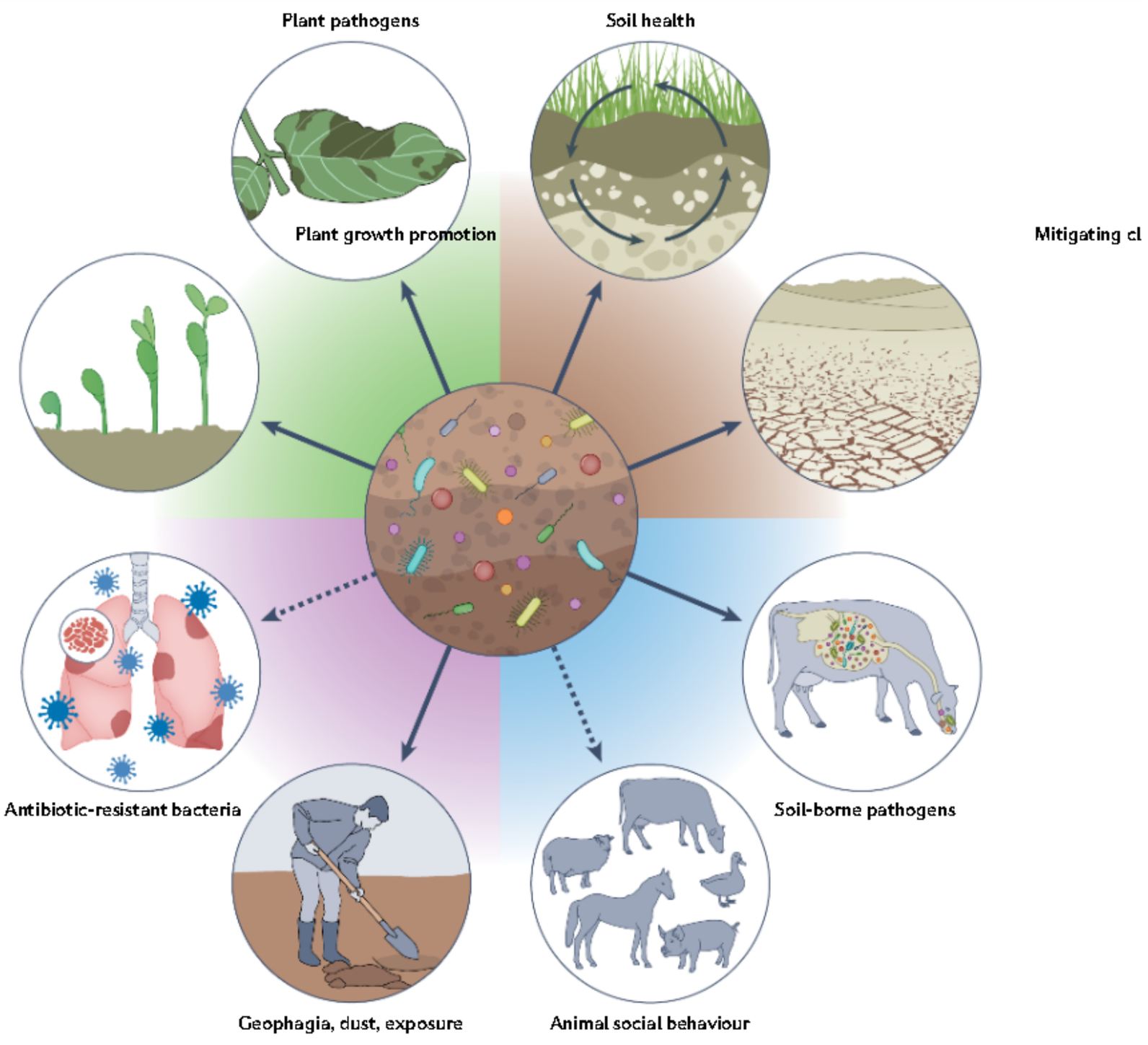
Human Health

- Human health is intimately connected to soil health
- **Ingestion of soil** is used to supplement a nutrient-poor diet, soil as a detoxifying agents for making some food products edible, as well as for medicinal reasons such as gastrointestinal treatments
- People with more exposure to natural environments are less likely to suffer from allergic reactions, which may be linked to soil microbiomes and inhalation of soil particles
- **Hygiene hypothesis** - small family size, intense hygiene, high antibiotic use and urban homes leads to allergy due to insufficient stimulation of immuno-regulatory circuits in people. Great global rise in allergies, autoimmune cond., asthma, atopic dermatitis and hay fever.
- **Biodiversity hypothesis** - predicts that children growing up in farming environments have reduced allergic sensitivity as they are already exposed to a higher microbial diversity

- Together, these hypotheses highlight the importance of natural environmental microbiomes for human health
- Soil microbiomes regulate the cycling of essential elements in plants and also the health of all plants
- Humans can only synthesise half of the essential amino acids themselves and depend on food intake for the remaining amino acids and essential vitamins. Plants only produce small amounts of **secondary metabolites**, but beneficial microorganisms associated with them can **enhance their production**, including **omega-3 (n-3) polyunsaturated fatty acids, linoleic acid, l-carnitine, choline or sphingomyelin.**
- Soil microbiomes are essential for **food security.**
- Soil microorganisms mediate a wide range of environmental processes and soil ecosystem services, including purification of drinking water, stabilization of soil aggregates, carbon storage and the production of greenhouse gases

- Healthy soils are linked to good soil structure, optimum nutrients and organic matter levels.
- Soil microbiomes have a demonstrable impact on plants and animals consumed by humans, and, by doing so, soils **indirectly influence human health.**
- More than **300 soil fungal species** are known to cause human disease. *Exserohilum rostratum* caused a fungal meningitis outbreak in the United States in 2012. Some protists can also cause human parasitic diseases, such as diarrhoea and amoebic dysentery
- Hookworm infection affects millions of people and causes more than 10,000 annual deaths worldwide
- Escherichia coli O157:H7 causes 73,000 infections per year in the United States and it can persist for more than 90 days in soil
- It is still unclear what proportion of the human microbiome is directly or indirectly linked to the soil microbial reservoir.

Fig2. How the soil microbiome influences one health



Influencing factors

Edaphic Factors - Factors related to soil properties

- Soil temperature, pH, moisture, redox status, organic carbon content and spatiotemporal heterogeneity are the major drivers of soil microbial communities, with feedback of their contributions to ecosystem processes and one health
- Soil pH is a key predictor of microbial community structure and composition at field to continental scales
- The ability of mycorrhizal fungi to forage for nutrients and deliver them to plants is directly linked to soil pH
- Soil Organic Matter has an overall positive effect on soil microbial diversity and community composition - is linked to the cycling and availability of other nutrients

Global change factors

- One of the strongest consequences of global climate change is increasing occurrences of drought. The decline of mycorrhizal fungi of trees owing to warming and drought can cascade below ground and accelerate SOM decomposition, reduce soil organic carbon content and alter ecosystem biogeochemistry
- The effect of elevated CO2 can be more complex and rising CO2 can differentially alter microbial ecophysiological strategies with divergent effects on different functional groups
- The proportional abundance of soil-borne pathogens may increase with rising temperature, altered humidity and precipitation
- Warming and altered humidity may enhance plant disease owing to a ‘microbial loop’
- A recent meta-analysis found that the net effects of global change factors (warming, elevated CO2, drought, fertilization and land-use change) on microbial alpha diversity are highly variable, with rare microorganisms more strongly affected by global change than the dominant taxa. These findings are important because several studies have shown that rare microorganisms drive pivotal ecosystem functions and contribute to ecosystem multifunctionality

Anti-microbial resistance

- Soil microbial communities and their contributions to one health are further threatened by **chemical pollution**, including microplastics, antibiotics and pesticides
- More than **700,000 people die** annually from antimicrobial-resistant infections with a projection of up to 10million by 2050
- As much as **32 tons** of third- and fourth-generation antibiotics are annually used in **meat and dairy industries**
- Large use of antibiotics has led to the spread of **antimicrobial resistance (AMR)** genes and soil is one of the sinks for AMR
- AMR genes can be detected **90 days** after application of AMR-contaminated manure in soils and can be transferred from manure-amended soils to vegetables

Land-use intensification

- The total area of cultivated land worldwide has increased by more than 500% in the past five decades with a 700% increase in fertilizer use and a several-fold increase in pesticide use
- Such intensive practices can reduce the diversity and complexity of microbiomes and negatively influence beneficial microorganisms in roots and soils
- Land-use intensification can cause **homogenisation** of soil microbial communities with the dominance of a few taxonomic and/or trophic groups and a decrease in the overall diversity
- The use of agrochemicals has increased by more than **40%** in recent years, with as much as **1.2 million tons of active pesticide** ingredients used annually
- Synthetic pesticides are widespread in soils and residues can be detected even after 20 years of organic management
- Pesticide residues had negative associations with the overall microbial biomass and **impaired the nutrient uptake** machinery of beneficial mycorrhizal fungi

One Health, dysbiosis and soil microbial diversity

- The positive effects of soil **microbial diversity** are explained by the fact that different microorganisms provide different functions.
- The resistance and resilience of soil microbiomes to disturbance is expected to increase with microbial diversity
- The disruption of microbiome homeostasis **(dysbiosis)** can cause impaired soil, plant and human health, and this is often linked to reduced microbial diversity, indicating the importance of biodiversity
- Maintaining a 'healthy state' requires '**eubiosis**' of soil microbial communities, which is typically associated with high diversity and uniformity of representative microbiota
- However, considering the remarkable dynamics and inherent complexity and instability of soil microbiomes, the task of identifying a healthy state can be daunting
- Importantly, a healthy microbiome is not, by definition, diverse. Although various studies report a positive link between soil microbial diversity and components of one health, there are also examples of no relationships and context dependencies.

- For example, many of the taxa in the gut microbiome belong to *Firmicutes* and *Bacteroidetes*, which together represent nearly **70% of the total microbiota**, and the dominance of a few taxa is adequate for usual functioning. Indeed, understanding the biology of a healthy microbiome state remains a major bottleneck

Outlook

- We highlight that microbial health is woven into one health because the health of each of its components is determined by microorganisms
- We demonstrate that soil microbiomes, directly and indirectly, influence plant, animal, human and environmental health, and thereby one health
- Studies have shown that land- use intensification, urbanization and landscape simplification cause homogenization of the soil micro biome and reduce soil microbial diversity

- Soil microbiomes in urban sites, compared with rural sites, contain more antibiotic-resistance genes and genes associated with human pathogens
- Animal livestock consumes the majority of the world's antibiotics - threat of antibiotic-resistant bacteria that can be distributed via seepage or manure to the environment
- Viruses may play a much more important role in soil communities than previously thought
- Chemical pollution is widespread - the soil microbiome is exposed to many chemical contaminants, including antibiotics, microplastics, heavy metals and pesticides
- Pathogen invasion is hampered when soil microbial diversity is high - it is still unclear whether impoverished microbial communities are less resistant to invasion
- Finally, whereas the state of above-ground biodiversity is easy to monitor and already assessed in many countries, underground processes are more difficult to study and far less understood.
- In view of the importance of the soil microbiome in determining the one health components (plant, animal, human and eco-system), we recommend that governments initiate and support systematic monitoring tools to investigate the trends, threats and long-term developments of the soil microbiome

Thank you!

Coalition of Health Professionals
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