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The new age of soil microbiome

Annamaria Bevivino,
Head of the ENEA Laboratory
SSPT-BIOAG-SOQUAS

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Microbiome: the new definition

Berg *et al. Microbiome* (2020) 8:103
https://doi.org/10.1186/s40168-020-00875-0

Microbiome

COMMENTARY Open Access

Microbiome definition re-visited: old concepts and new challenges

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The microbiome vs. the microbiota

The **microbiome** is defined as a characteristic microbial community occupying a reasonable, well defined habitat which has distinct physio-chemical properties. The microbiome not only refers to the microorganisms involved but also encompass their theatre of activity, which results in the formation of specific ecological niches. The microbiome, which forms a dynamic and interactive micro-ecosystem prone to change in time and scale, is integrated in macro-ecosystems including eukaryotic hosts, and here crucial for their functioning and health.

The **microbiota** consists of the assembly of microorganisms belonging to different kingdoms (Prokaryotes [Bacteria, Archaea], Eukaryotes [e.g. Protozoa, Fungi, Algae]), while "their theatre of activity" includes microbial structures, metabolites, mobile genetic elements (e.g. transposons, phages, viruses) as well as relic 816 DNA embedded in the environmental conditions of the habitat.

- MICROBIOME DEFINITION -

microbiome support

Microbiota

Microbiome

Soil and plant microbiome

- Microbes, like bacteria, yeasts and other fungi, occur everywhere in the food system.
- Communities of microbes are essential in plant, animal, human and environmental health, with a consequent impact in terms of crop and livestock productivity, food quality and safety as well as for food waste decomposition and recycling processes.
- The composition of microbe communities differ across the food system, depending on the environmental conditions.

Soil microbes underpin food quality and security

- Soil is a complex and dynamic biological system
- Soil is essential for the maintenance of biodiversity above and below ground
- Soil governs plant productivity of terrestrial ecosystems and it maintains biogeochemical cycles
- Soil is where food begins: 95% of all food comes from the soil
- Soil is fundamental to crop production
- Soil would be more resilient, and farmers would be less dependent on toxic pesticides and chemical fertilizers.

Simplified schematic of soil horizon and soil macro- and microaggregates

- Soils can generally be viewed as a complex three-dimensional structure consisting of packed aggregates and pore spaces
- Aggregates comprise clusters of mineral particles and organic carbon
- The architecture of a particular soil influences interactions between plants, microbes, and the soil matrix
- The porosity and connectivity of aggregates are influenced by the diversity of bacteria and fungi present during formation

Wilpiszeski et al. Applied and Environmental Microbiology Jul 2019, 85 (14) e00324-19

Embracing the unknown: disentangling the complexities

Fierer, 2017. *Nature Microbiol*. doi:10.1038/nrmicro.2017.87

Nature Reviews | Microbiology

- Soil is not a single environment; instead, soil encompasses a broad range of different microbial habitats.
- These include the rhizosphere (soil in close proximity to plant roots; part a), surface layers that are exposed to light (part b; the photic zone), soil associated with earthworm burrows (the drilosphere; part c), and soil found in preferential water flow paths, including cracks in the soil (part d).
- One gram of healthy soil usually contains a microbiome comprising many millions of microbes, including archaea, bacteria and fungi.

The world beneath our feet

- The wealth of biodiversity below ground is vast and unappreciated: millions of microorganisms live and reproduce in a few grams of topsoil, an ecosystem essential for life on earth
- Soil microorganisms play an essential role in ecosystem functioning, decomposing organic matter, in determining the release of mineral nutrients, and in nutrient cycling
- Changes in soil microbial community may directly affect soil ecosystem function, particularly carbon and nitrogen cycling

Modified from Johannes Sikorski SOIL ORGANISMS 2015

Fierer, 2017. *Nature Microbiol.* doi:10.1038/nrmicro.2017.87

- The microbial biomass consists mostly of bacteria and fungi, which decompose crop residues and organic matter in soil. This process releases nutrients, such as nitrogen (N), sulfur (S) and, to a lesser extent, phosphate (P) into the soil that are available for plant uptake.

Microbial interaction

Microbial interactions visualized through microbial co-occurrence networks.

a Microbial interactions are influenced by environmental factors and are separated into positive, neutral, and negative interactions types.
b Microbial co-occurrence and co-exclusion networks help visualizing microbial interactions. In such networks, nodes usually represent taxa of microorganisms, and edges represent statistically significant associations between nodes. Green edges usually stay for positive interactions, while red edges visualize negative interactions between the microorganisms.
cTesting of the hypotheses resulted from the network analyses in relevant model systems is required for a comprehensive study of microbial interactions

Soil microbes: networking

frontiers in Microbiology
REVIEW
published: 05 June 2018
doi: 10.3389/fmicb.2018.01006

Belowground Microbiota and the Health of Tree Crops

Jesús Mercado-Blanco[1], Isabel Abrantes[2], Anna Barra Caracciolo[3], Annamaria Bevivino[4], Aurelio Ciancio[5], Paola Grenni[3], Katarzyna Hrynkiewicz[6], László Kredics[7] and Diogo N. Proença[8]*

Arrows show negative effects (A), such as predation, parasitism, pathogenicity or (B) positive links, such as growth promotion, symbiosis or alimentary provision.

A simplified food web describing main soil components and their relationships. The nodes are classified by roles as: primary root (dark green), beneficial soil components, organisms or promoters, including soil factors (blue), decomposers (brown), pathogens (orange) and biocontrol agents or antagonists (pale green).

Healthy soil for a healthy life

- The healthiest soils are those with a diversity and abundance of life
- The use of beneficial microbes represents a promising tool that may respond to the challenges for modern agriculture

Bulk soil vs. rhizosphere

- In 1904, Lorenz Hiltner first coined the term "rhizosphere" to describe the plant-root interface
- The rhizosphere is the area around a plant root that is inhabited by a unique population of microorganisms influenced by the chemicals released from plant roots
- This complex plant-associated microbial community, also referred to as the second genome of the plant, is crucial for plant health.

REVIEW ARTICLE

The rhizosphere microbiome: significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms

Rodrigo Mendes[1], Paolina Garbeva[2] & Jos M. Raaijmakers[3]

[1]Laboratory of Environmental Microbiology, Embrapa Environment, Jaguariuna, Brazil; [2]Netherlands Institute of Ecology, Royal Dutch Academy of Arts & Sciences (NIOO-KNAW), Wageningen, The Netherlands; and [3]Laboratory of Phytopathology, Bacterial Ecology & Genomics, Wageningen University, Wageningen, The Netherlands

Root secretions change with root age: Simple organic acids, then to complex phenolics

Root secretions benefit plants directly: organic acids mobilise plant nutrients, secretions kill soil pathogens.

Plant root secretions actively manage the root microbial environment: they are signals that can stimulate or suppress beneficial or harmful microbes.

Berendsen et al (2012), Trends in Plant Science 17, 478-86.

Rhizosphere soil compared to bulk soil: up to 40% of plant carbon photosynthates are secreted into soil via roots, so there can be abundant food for microbes and fungi here compared to bulk soil.

The rhizosphere

- The **rhizosphere** is a dynamic region governed by complex interactions between plants and the organisms that are in close association with the root.
- The rhizosphere includes **three zones** which are defined based on their relative proximity to the root
- **Endorhizosphere**: includes portions of the cortex and endodermis
- **Rhizoplane**: the medial zone directly adjacent to the root including the root epidermis and mucilage
- **Ectorhizosphere** which extends from the rhizoplane out into the bulk soil

https://www.nature.com/scitable/knowledge/library/the-rhizosphere-roots-soil-and-67500617/

Bulk soil vs. rhizosphere

Microbes are recruited from the bulk soil to the rhizosphere by root exudates, which include primary metabolites mainly responsible for attraction and secondary metabolites mainly responsible for screening the recruited microbes.

- The bulk soil microbial community is the seed bank for the plant root-associated microbiota.
- Rhizosphere community has greater microbial biomass and activity compared with that in bulk soil.

Factors driving the assembly of the rhizosphere microbiota

- The assembly of the rhizosphere microbiota is governed by the abiotic factors, soil properties, climate, and biotic factors of plant species, biotic interactions and agricultural management.

The rhizosphere microbiome: the function

- Schematic overview of the functions and impact of plant beneficial ('the good'), plant pathogenic ('the bad'), and opportunistic human pathogens ('the ugly') on the host plant

Ali et al. (2017) The Good, the Bad, and the Ugly of Rhizosphere Microbiome. In: Kumar V., Kumar M., Sharma S., Prasad R. (eds) Probiotics and Plant Health. Springer, Singapore.

The 'Plant Microbiome'

Uwe Stroeher. The Plant microbiome. Australian Agronomist Magazine's Spring 2019

The 'Plant Microbiome' can be described as the sum total of the genomic contribution made by the diverse microbial communities that inhabit the surface and internal tissues of the plant parts.

The concept of «Holobiont»

Based on: *Gopal M and Gupta A (2016) Front. Microbiol. 7:1971. doi: 10.3389/fmicb.2016.01971*

- In the ecological perspective, the plant holobiont and not the plant as an individual, is now known to respond to the various biotic and abiotic perturbations in a given environment.
- Plant-associated microbiome is important for plant growth, health and stress resilience

The One Health concept

Precision agriculture & personalised medicine

- The use of microbiome-based therapies represents a promising tool that may respond to the challenges for translational medicine

- The use of beneficial microbes represents a promising tool that may respond to the challenges for modern agriculture

How can restore the sustainability of agricultural systems ?

Soil organisms are an integral component of ecosystems, but their activities receive little recognition in agricultural management strategies.

- Stimulating soil life and internally regulated ecosystem porcesses
- Enhance and maintain the soil biodiversity and function
- Inoculation with key microbiota members
- Targeted manipulations of soil organisms

Bender et al. Trends Ecol Evol. 2016 Jun;31(6):440-452.

Soil microbiome as a solution

- **Understanding soil-root microbiome diversity and function** to uncover novel microbes that can be used as biofertilisers and biopesticides
- **Promoting crop–microbe associations** through the development and optimisation of microbial inocula
- **Enhancing beneficial soil microbiome** diversity and function through optimising soil management methods

Compant *et al.*, 2019 *J Adv Res 19:29-37*

Microbiome engineering

A targeted soil biological engineering approach to improving ecosystem functioning and services.

Microbial strains with verified function can be combined into simple synthetic microbiomes containing few to several dozen species and use to promote plant health and improve soil fertility

frontiers in Plant Science

OPINION
published: 04 December 2018
doi: 10.3389/fpls.2018.01801

Check for updates

Microbial Consortia: Promising Probiotics as Plant Biostimulants for Sustainable Agriculture

Sheridan L. Woo [1,2,3] and Olimpia Pepe [3,4,5]**

[1] Department of Pharmacy, University of Naples Federico II, Naples, Italy, [2] National Research Council, Institute for Sustainable Plant Protection, Portici, Italy, [3] Task Force on Microbiome Studies, University of Naples Federico II, Naples, Italy, [4] Department of Agricultural Sciences, University of Naples Federico II, Portici, Italy, [5] CIRAM-Interdepartmental Center for Environmental Research, University of Naples Federico II, Naples, Italy

Targeted and untargeted management of soil microbial diversity

- The development of high-throughput technologies applied to the study of soil microbial functional diversity will help strengthen the link between soil well-being, food quality, food safety and human health.

Bertola et al. Improvement of Soil Microbial Diversity through Sustainable Agricultural Practices and Its Evaluation by -Omics Approaches: A Perspective for the Environment, Food Quality and Human Safety. *Microorganisms* 2021, *9*, 1400.

Microbial consortia for sustainable crop systems

- Microbial consortia have a higher potential to increase plant growth-promoting (PGP) effects compared to single inoculants

Microbial consortia» indicates not only living together but also

- division of labor among members to increase community efficiency and productivity
- interactions between members at various scales of time and space (physical contact, chemical signaling and metabolic exchange)

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Microbiome-based solutions in SIMBA project

SIMBA
SUSTAINABLE INNOVATION OF MICROBIOME APPLICATIONS IN THE FOOD SYSTEM

Seaweed extracts, Plant-derived protein hydrolysate

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microorganisms MDPI

Article

Identification of Beneficial Microbial Consortia and Bioactive Compounds with Potential as Plant Biostimulants for a Sustainable Agriculture

Silvia Tabacchioni [1,†], Stefania Passato [2], Patrizia Ambrosino [2], Liren Huang [3], Marina Caldara [4], Cristina Cantale [1,†], Jonas Hett [5], Antonella Del Fiore [1], Alessia Fiore [1], Andreas Schlüter [3], Alexander Sczyrba [3], Elena Maestri [4], Nelson Marmiroli [4], Daniel Neuhoff [5], Joseph Nesme [6], Søren Johannes Sørensen [6], Giuseppe Aprea [1], Chiara Nobili [1], Ombretta Presenti [1], Giusto Giovannetti [7], Caterina Giovannetti [7], Anne Pihlanto [8], Andrea Brunori [1] and Annamaria Bevivino [1,*]

fermentation MDPI

Article

Designing a Waste-Based Culture Medium for the Production of Plant Growth Promoting Microorganisms Based on Cladodes Juice from *Opuntia ficus-indica* Pruning

Rosaria Alessandra Magarelli [1], Mario Trupo [1,*], Alfredo Ambrico [1,*], Vincenzo Larocca [1], Maria Martino [1], Salvatore Palazzo [1], Roberto Balducchi [1], Vesa Joutsjoki [2], Anne Pihlanto [2] and Annamaria Bevivino [3]

From PGPM selection to scaling-up microbial production

Delivery methods

Microbial consortia were applied *via* seed coating or delivered as a powder (with zeolite-based amendments), liquid suspension or incorporated in wood biochar, with or without arbuscular mycorrhizal fungi (AMF).

From LAB to FIELD

Lab/Climate chamber

Picture: www.weiss-technik.com

Greenhouse

Picture : Jonas Hett

Field

Picture : Jonas Hett

Environmental impacts
Experimental size
Variance
Relevance

Standardized environment
Reproducibility
Significance

Microbial research levels, significance versus relevance

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From microbial production to application in greenhouse and field

agronomy MDPI

Article

Effects of Multi-Species Microbial Inoculants on Early Wheat Growth and Litterbag Microbial Activity

International Journal of Molecular Sciences

Article

A Metagenomic and Gene Expression Analysis in Wheat (*T. durum*) and Maize (*Z. mays*) Biofertilized with PGPM and Biochar

Sara Graziano [1], Marina Caldara [2], Mariolina Gullì [1,2], Annamaria Bevivino [3], Elena Maestri [1,2] and Nelson Marmiroli [1,2,4,*]

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Impact of microbial consortia on organic maize in a temperate climate varies with environment but not with fertilization

Jonas Hett [a], Thomas F. Döring [a], Annamaria Bevivino [b], Daniel Neuhoff [a,*]

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