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THE SOIL MICROBIOME A GAME CHANGER FOR FOOD AND AGRICULTURE

Executive summary for
policymakers and
researchers



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Jennifer Kendzior, Dylan Warren Raffa, Anne Bogdanski

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Context

This is an executive summary of *A review of the impacts of crop production on the soil microbiome: Innovations and policy recommendations to address environmental degradation, climate change and human health* (Kendzior, Warren-Raffa and Bogdanski, 2022), available at <https://www.fao.org/3/cb8698en/cb8698en.pdf>.

The information and analyses in the full review are based on two separate literature reviews conducted by the Food and Agriculture Organization of the United Nations (FAO). First, a narrative review provides a general description of how different crop production practices can impact the soil microbiome. Second, a systematic review of over 2 000 scientific publications explores whether there is solid, scientific evidence of strong connections between crop production practices, the soil microbiome and climate change or human health. The conclusions drawn from the

literature reviews were discussed and expanded upon during a timely series of virtual conferences in July 2020 (Microbiome: The Missing Link(s) Virtual Learning Pathway). The participants included microbiome experts from different disciplines as well as different sectors (academic, industry, and policymaking). The conclusions further benefited from expert meetings held with the Food System Microbiome Working Group of the European Commission-led International Bioeconomy Forum and the FAO-led International Sustainable Bioeconomy Working Group.

The purpose of this executive summary is to present the main findings, proposed next steps and specific policy recommendations that can help inform future policy and applied research on soil microbiome issues related to climate change, environmental degradation and human health.

FAO microbiome working group

Produced by the informal FAO microbiome working group, this review is among the first of several publications that address different microbiome ecosystems and their relatively underexplored potential to alleviate global problems. Following numerous discussions with microbiome experts from industry, academia, and policymaking, a key message has emerged: FAO's unique role as an interface between science, innovation and policy at global, regional, national and local levels positions it as an important driver of change in this field.

The authors are grateful for the essential contributions by participants in the Microbiome Missing Link Learning Pathway (July 2020). This virtual event of seminars and workshops was made possible by the contribution of numerous microbiome experts from academic, private, and policy sectors across the world, including those from Agroscope (Switzerland), China Agricultural University, the European Commission, the Food and Agriculture Organization of the United Nations, the Global Initiative of Crop Microbiome and Sustainable Agriculture, Louvain Drug Research Institute (Belgium), MicrobiomeSupport (European Union), National Genomics Research and Development Initiative (Canada), National Institutes of Health (United States of America), Rutgers State University of New Jersey (United States of America), Stanford University School of Medicine (United States of America), University of Bologna (Italy), University of California San Diego (United States of America), University of Pretoria (South Africa), University of Zurich (Switzerland), Wageningen

University (Netherlands), and Western Sydney University (Australia).

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INTRODUCTION

Humanity and the planet are grappling with extraordinary challenges. These include unsustainable production and consumption patterns, biodiversity loss, climate change, malnutrition, pollution, and a rise in diet-related, non-communicable diseases such as obesity, heart disease, and diabetes. Unsustainable agrifood systems are a major driver of all of these.

It is important to underline that **these challenges are interdependent**. Malnutrition includes undernutrition, micronutrient deficiencies, excess intake of dietary energy, overweight and obesity, and a range of non-communicable diseases associated with unhealthy diets. Although sustainable agrifood systems are key to fighting problems of malnutrition, the way they are managed also impacts other fundamental issues such as diminishing land availability, increasing soil degradation, pollution, and biodiversity loss. Climate change adds another layer of pressure: both slow onset and abrupt events imply shifts

in ecosystems as well as impacts from more frequent and severe weather events.

In other words, the challenges mentioned above are part of different but **interconnected systems** (e.g. climate system, food production system, farm or landscape ecosystem) that have multiple **dimensions** (e.g. social, economic, cultural, political, environmental) and can be described at different **scales** (e.g. local, national, regional, global). That is why **systemic approaches** are increasingly being called upon to recognize and understand the intricacies and multiple layers inherent in these challenges. For instance, One Health is a well-known framework commonly used to acknowledge interconnections between different ecosystems, across different domains covering human, animal, and environmental health. One Health plays a central role in addressing major global challenges such as antimicrobial resistance, which builds on our growing understanding of microorganisms, their functions and interactions across different ecosystems.

1.1 BIOECONOMY – A SYSTEMIC APPROACH TO ADDRESS INTERDEPENDENT CHALLENGES

Another overarching framework that aims to address multiple, interconnected challenges is **bioeconomy**. Bioeconomy describes a knowledge-intensive economic activity involving the use of biosciences and biotechnologies in the production and management of goods, services and energy, with the aim of promoting environmental and social benefits. While there is no internationally agreed definition, the bioeconomy is often referred to as the production, utilization, conservation, and regeneration of biological resources – including related knowledge, science, technology, and innovation – to provide sustainable solutions within and across all economic sectors and enable a transformation to a sustainable economy.¹

The sustainable bioeconomy has in fact been recognized as a leading framework for agrifood systems transformation by the Scientific Group of the United Nations Food Systems Summit, convened in September 2021. It is against this background that FAO takes a holistic and inclusive approach to the application of bio-innovations – including agrifood innovations – across our entire agrifood systems. Within this sphere, one of the areas that may offer game-changing solutions is microbiome science, technology, and innovation (STI).

Microbiome STI is showing exciting potential to provide sustainable solutions that leverage the knowledge and concrete applications emerging from the fast-growing microbiome research and development field. **Agrifood systems around the world stand to gain from the enormous potential of microbiome STI, supported by a circular and sustainable bioeconomy framework.**

This review specifically focuses on the soil microbiome.

1.2 A SOIL MICROBIOME PERSPECTIVE

What is the soil microbiome? Let's start with **soil microbiota**, which are the living bacteria, archaea, fungi, algae, and protozoa that inhabit the soil. Add to them “their theatre of activity”, meaning the microbial structures, metabolites, mobile genetic elements (e.g. viruses and phages), and relic DNA found in the soil habitat, and we have the **soil microbiome** (Berg *et al.*, 2020).²

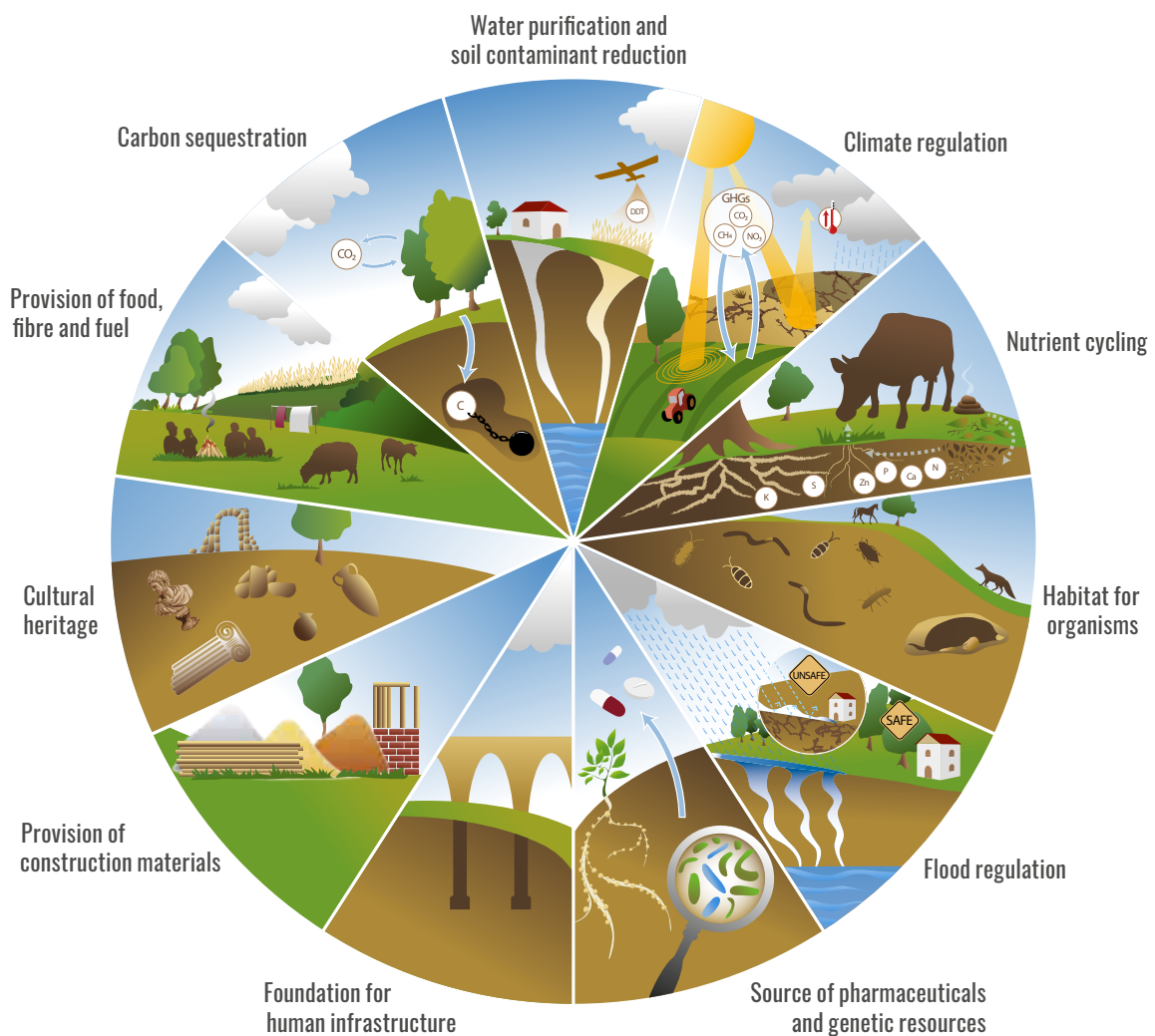
It is increasingly acknowledged that, although invisible to the naked eye, the soil microbiome plays a fundamental role in the relationships between healthy soils, climate and people (**Figure 1**). It is therefore critical that accurate and up-to-date knowledge in this field is made available to inform policy that addresses the multifaceted challenges described in the introduction. At the global level, this includes policies that support the role that healthy soils play in achieving the Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development, as well as contributing to other important global initiatives such as the United Nations Decade on Ecosystem Restoration and the Global Soil Partnership. The importance of conserving microbial biodiversity for healthy and functional soils is recognized by the intergovernmental bodies dealing specifically with soils and biological diversity for food and agriculture, the FAO-led Commission on Genetic Resources for Food and Agriculture (CGRFA) and the Intergovernmental Technical Panel on Soils (ITPS). However, describing the complexity of the soil microbiome has until now been a difficult task given knowledge gaps in this burgeoning scientific field. There was no comprehensive review of the importance of the soil microbiome, or of the effects of crop production practices on the soil microbiome and their linkages with climate change and human health.

Thankfully, boosted by advances in new analytical innovations, research into the soil microbiome is now growing exponentially. These advances have enabled the publication of the **major new review** on which this

executive summary is based, which for the first time presents a more holistic picture of the interlinkages between the soil microbiome, crop production practices, climate change, ecosystem health and human health.

FIGURE 1.

KEY SOIL FUNCTIONS THAT SUSTAIN LIFE ON EARTH.



Source: adapted from FAO. 2015. *Soils deliver ecosystem services that enable life on Earth – Infographics*. <https://www.fao.org/publications/card/en/c/0815e457-c6a4-47e9-ab6c-f23224279834>

1.3

AIMS OF THE REVIEW

This review of the impacts of crop production on the soil microbiome, and causal impacts on climate change and human health, aims to provide **access to the best scientific knowledge available about microbiome innovations and risks** to the scientific community, policymakers, private sector actors and consumers.

To this end, the review aims to answer five main questions, deemed critical for future agricultural policies.

THE MAIN QUESTIONS EXPLORED IN THIS REVIEW

- ▶ Why does the soil microbiome matter for a healthy planet and people? Specifically, what are the relationships between:
 - ▶ The soil microbiome and climate change?
 - ▶ The soil microbiome and human health?
- ▶ What are the impacts of crop production practices on the soil microbiome?
- ▶ Does scientific literature show any significant, causal impacts of crop production practices and the soil microbiome on climate change or human health?
- ▶ From a research perspective, which research and development issues need further investigation from a microbiome perspective?
- ▶ From a policy perspective, is there any solid evidence that can and should inform policy?

The current review investigates **how nine specific crop production practices can impact the soil microbiome, and how this might affect human health and climate change**. It then explores how that knowledge can be applied in practice, in the context of a circular and sustainable bioeconomy. Given the tension between the vast and exciting potential of soil microbial applications, on the one hand, and the technical and ethical questions related to their use and commercialization, on the other, the review concludes with a discussion of the challenges to overcome and with policy recommendations to move forward.

THE NINE CROP PRODUCTION PRACTICES EXPLORED IN THE LITERATURE REVIEW

- ▶ Land use
- ▶ Tillage
- ▶ Agroecosystem diversity (plant diversity, crop rotations, cover crops)
- ▶ Crop residue management
- ▶ Plant variety selection
- ▶ Irrigation
- ▶ Fertilization
- ▶ Pest management
- ▶ Microplastics in agricultural soils

MAIN FINDINGS

2.1 THE SOIL MICROBIOME: HOW IS IT RELATED TO HEALTHY SOILS, CLIMATE AND PEOPLE?

Soil microbial ecosystems are likely the most **genetically diverse** communities on the planet. The composition of a given community varies widely, as does its distribution throughout a given soil habitat. This is due to the soil microbiome's diversity and multiple interactions with the environment, climate and soil modifications, which result in constantly evolving micro-ecosystems.

While we still understand relatively little about the soil microbiome, the immense genetic variety and the diverse ecosystem functions that soil microorganisms perform are evident.

This diversity is fundamental in ensuring the delivery of a wide range of **ecosystem services** (**Figure 2**), including provisioning of clean water and air, food and raw materials, recreational space and biodiversity.

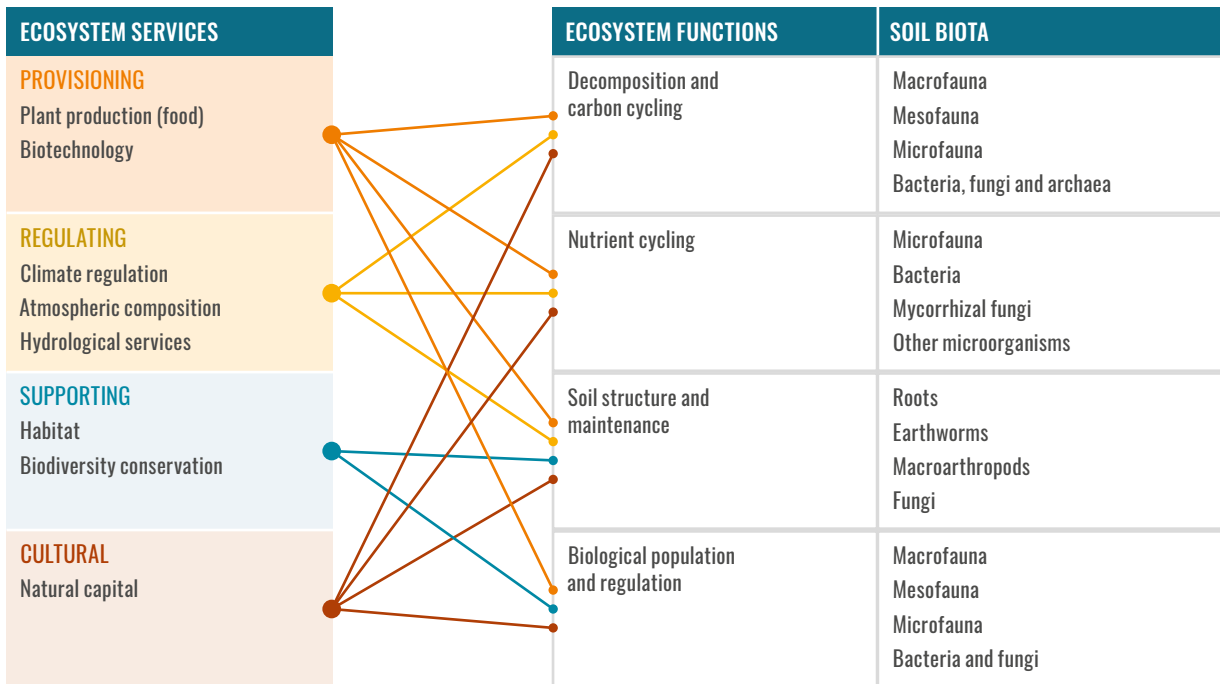
Furthermore, the soil microbiome is involved in the planet's **climate system**, because it is a direct driver of terrestrial greenhouse gas fluxes and soil carbon dynamics (**Figure 3**).

In addition, there are strong theoretical arguments and some evidence of a direct relationship between the soil microbiome and **human health** (see 2.2 for more).

FIGURE 2.

SOIL-BASED ECOSYSTEM SERVICES, AND THE ECOSYSTEM FUNCTIONS AND SOIL BIOTA THAT SUPPORT THEM.

Ecosystem functions are the underlying processes that produce ecosystem benefits acquired by human society, known as ecosystem services.



Source: Orgiazzi, A., Bardgett, R.D., Barrios, E., Behan-Pelletier, V., Briones, M.J.I., Chotte, J.-L., De Deyn, G.B. *et al.*, eds. 2016. *Global soil biodiversity atlas*. Luxembourg, Publications Office of the European Union. 176 pp. <https://data.europa.eu/doi/10.2788/799182>

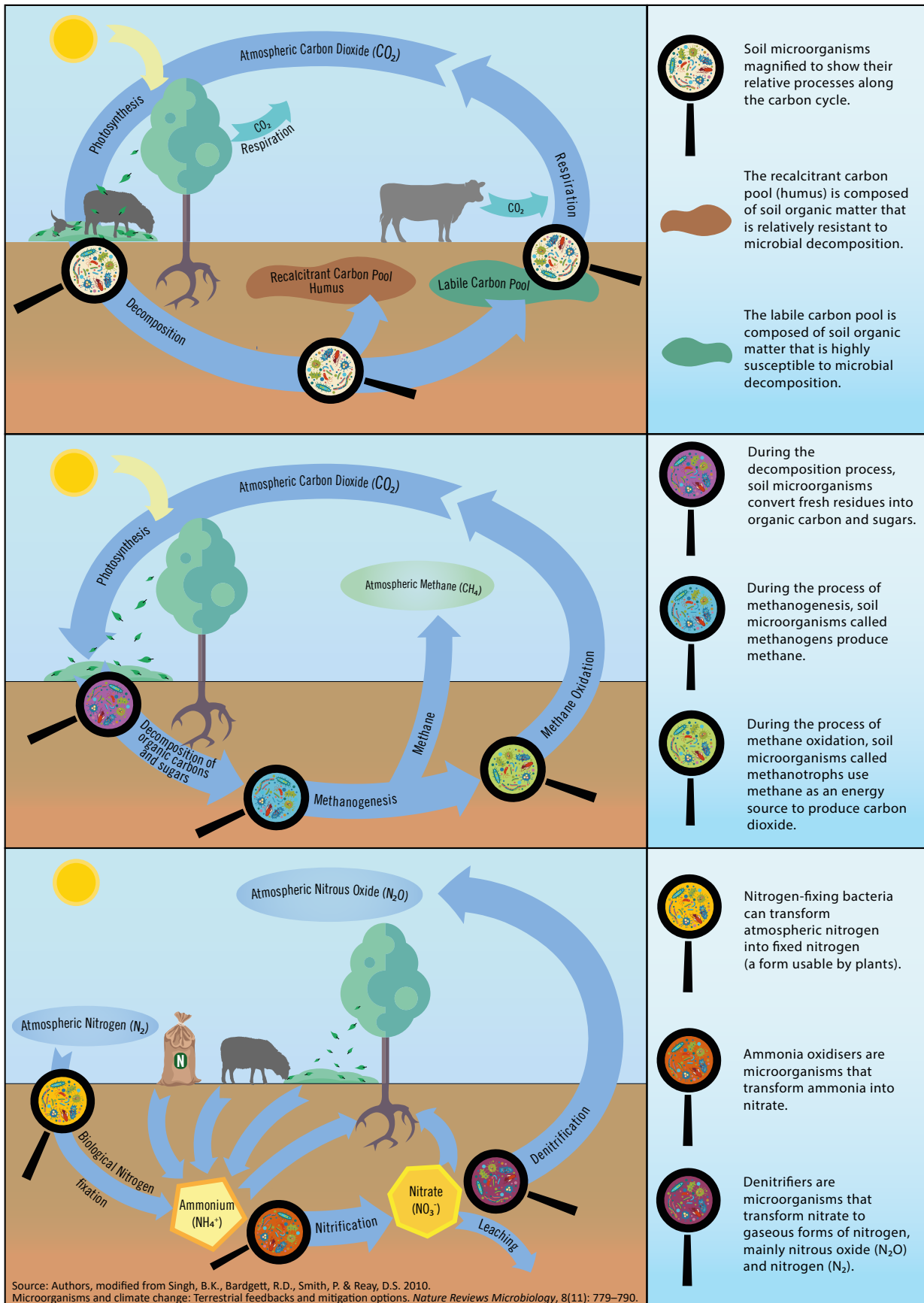
Changes in the soil microbiome can cause changes in soil functions. For instance, if the type and number of microbial species are altered, the activities they perform may consequently differ. It is expected that ecosystems experience some fluctuation. However, profound, widespread changes can have significant and long-term, negative implications, potentially reaching tipping points. The next section presents key findings on how the nine specific crop production practices reviewed impact the soil microbiome, and what the ensuing effects might be on climate change and human health.

2.2 WHAT DO WE KNOW ABOUT HOW CROP PRODUCTION PRACTICES IMPACT THE SOIL MICROBIOME, CLIMATE CHANGE AND HUMAN HEALTH?

It is known that **different crop production practices can have a significant effect on the soil microbiome** (Table 1). Taking a step beyond these effects, **how might crop production practices modify the soil microbiome and, in turn, impact climate change or human health?** At present, it is difficult to predict how shifts in the soil microbiome will affect climate change.

FIGURE 3.

SOIL MICROORGANISMS ARE DIRECT DRIVERS OF BIOGEOCHEMICAL CYCLING INVOLVED IN TERRESTRIAL GREENHOUSE GAS EMISSIONS (CARBON DIOXIDE, METHANE AND NITROUS OXIDE).



The question is very broad and involves many, interacting biotic and abiotic factors. However, **there is solid, scientific evidence that demonstrates strong connections between some crop production practices, the soil microbiome, and their combined effects on greenhouse gas fluxes and soil carbon storage (Figure 3).** These practices include tillage, fertilization, and agroecosystem crop diversification. **The direct relationship between the soil microbiome and human health remains to be established, although the conceptual framework of likely connections is strong.**

Bringing these ideas into the context of real-life practice, two points are especially important to keep in mind. One is that any choice of farming practice will imply trade-offs between investments and returns. These need to be considered because crucial benefits may be apparent only in the long term, while remaining less so in the short term, resulting in less obvious incentive to change. For example, developing good soil structure requires knowledge, potential investment in inputs, time and related costs. Although adjusting to a significant shift in management may be costly in the short term, the benefits to the farming system may well pay out in the longer term: good soil structure encourages important soil functions such as nutrient cycling and storing,

biological productivity, and regulating water flow, as well as reducing erosion. A second point is that this review explores agricultural practices individually, and therefore does not capture the complexity of interactions of crop production practices. Systemic approaches that combine specific agricultural practices, such as conservation agriculture, are beyond the scope of this review.

We still have so much to learn about the soil microbiome; in fact, less than 1 percent of soil microbiome genetic diversity and functions have been studied so far. And there is at least as much mystery about the complex interactions between the soil microbiome, mesofauna and macrofauna, plants and abiotic aspects of the soil environment.

Even so, *what we do know* – as systematically brought together for the first time in this review – is that the **soil microbiome plays a pivotal role in ecosystem health, agroecosystems and the climate system.** The question now is what can – and should – we do with this ever-growing body of knowledge? How can we use it most beneficially for agroecosystem design and management, combining goals related to both food and nutrition security, and the environment? And, as the United Nations agency leading global efforts to promote agrifood systems transformation, what role can FAO play?

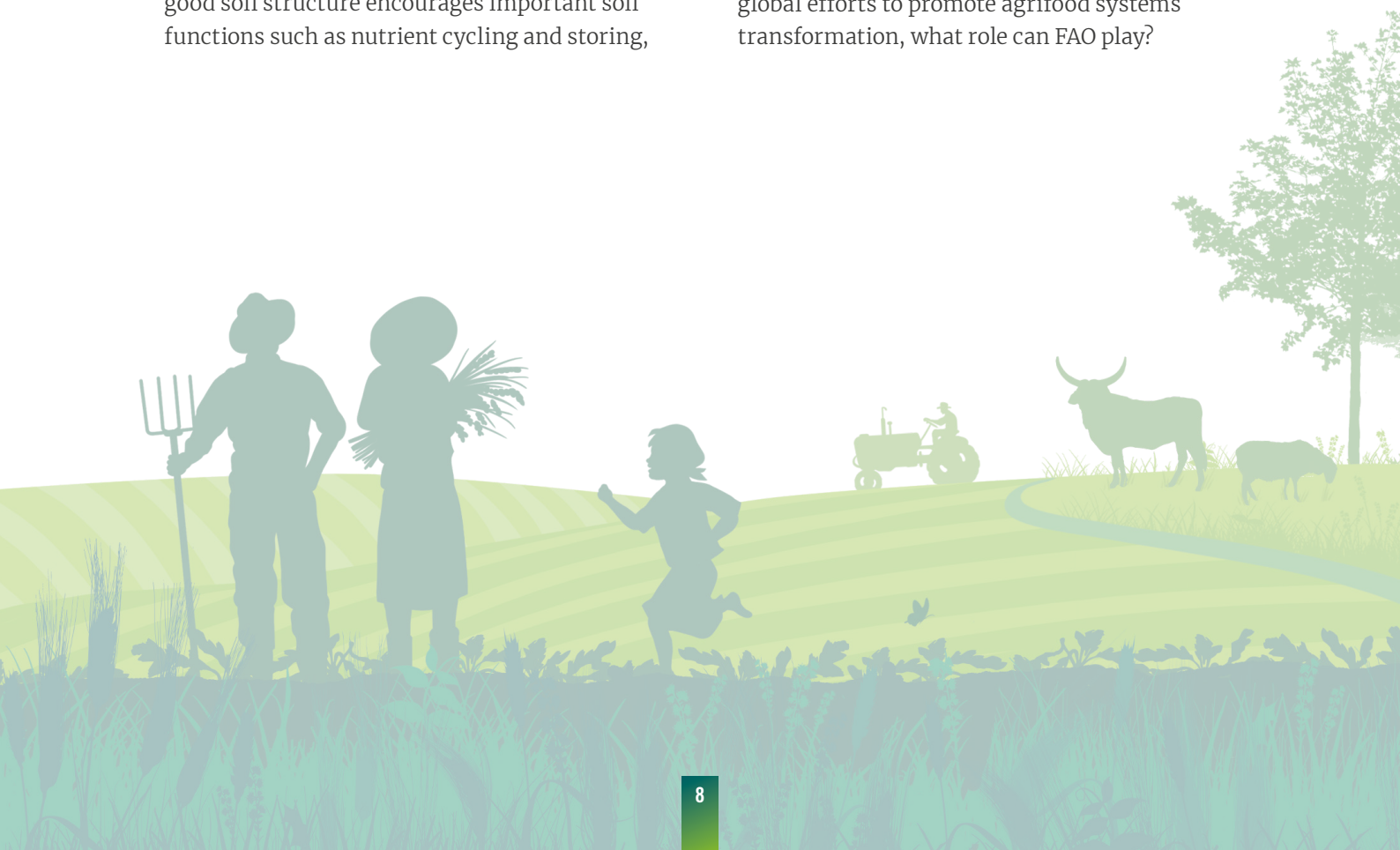


TABLE 1.

CROP PRODUCTION PRACTICES AND THEIR EFFECTS ON THE SOIL MICROBIOME: EVIDENCE-BASED EXAMPLES FROM THIS REVIEW

CROP PRODUCTION PRACTICE	EFFECTS ON THE SOIL MICROBIOME: EVIDENCE-BASED EXAMPLES FROM THIS REVIEW
LAND-USE CHANGES (e.g. deforestation for crop production)	Can affect soil microbial populations (e.g. their abundance and diversity) as well as their functional roles in the soil ecosystem. In some cases, the impact of land-use change can actually be stronger than extreme meteorological events such as drought.
EXCESSIVE TILLAGE	Usually negatively affects soil microbial communities, causing changes in their composition by affecting both bacterial and fungal populations. This can consequently influence soil functioning, plant productivity and provisioning of certain ecosystem services.
AGROECOSYSTEM DIVERSIFICATION INCLUDING PLANT DIVERSITY, CROP ROTATIONS AND COVER CROPS	A central point regarding agroecosystem diversification is that plants can also influence the soil microbiome through their different biochemical compositions (e.g. nutrients and metabolites). They are introduced into the soil via plant and root litter and root secretions. Studies have reported positive or no effects of plant diversity on soil microorganisms; crop rotations seem to result in improved soil health and related ecosystem services; and cover crops can impact soil microorganism communities, including fungi and arbuscular mycorrhiza, with possible improved ecosystem resilience.
CROP RESIDUES	Their impact on the soil microbiome remains inconclusive, the reviewed studies reporting positive, minor or no effects.
PLANT VARIETY SELECTION	Impacts the soil microbiome because plant genotypes influence the biochemistry of root secretions and root architecture. This, in turn, shapes the selection of microorganisms that live in the root zone (rhizosphere). Alteration of plant genotypes throughout the process of plant domestication has led to potential “missing microbes” in the root, rhizosphere and soil microbiomes.
IRRIGATION	Directly changes soil abiotic properties and can indirectly modify the root zone environment (rhizosphere) by influencing root litter and root secretions. This indirect effect can shape communities of microorganisms that promote crop growth and disease control. In addition, treated wastewater can carry bacteria with antimicrobial-resistant genes, causing concerns about how irrigation with such water sources impacts the soil resistome (the total assemblage of antimicrobial-resistant genes, antiseptic genes and heavy metal resistant genes found in the microbial ecosystem of a given soil).
FERTILIZERS	Both inorganic and organic fertilizers can affect the soil microbiome directly (e.g. as a source of nutrients) and indirectly (e.g. through positive effects on plant growth and development). Organic fertilizers can contribute microorganisms (e.g. through manure or compost applications), substantial carbon and other nutrients, and are therefore considered important for long-term soil fertility and soil functions. However, there are concerns and unanswered questions regarding how trace element accumulation, antimicrobial-resistant genes and antibiotic residues – introduced through manure fertilizer – impact the soil resistome.
PESTICIDES	Can impact the soil microbiome, significantly increasing or decreasing soil microbial communities, activities and biomass; less commonly, they can also have no detectable effect. These effects can drive selection for soil microbial species that can degrade pesticide compounds, leading to concerns about increased antimicrobial-resistant genes in the soil.
MICROPLASTICS IN AGRICULTURAL SOILS	Studies on microplastics in agricultural soils show mixed results, including no effects on the soil microbiome. However, microplastics do form a distinct microhabitat and consequentially can potentially impact soil microorganism communities and functioning.

NEXT STEPS: HOW TO BRIDGE THE GAP BETWEEN SOIL MICROBIOME SCIENCE, INNOVATION AND POLICY?

3.1 PRIORITY KNOWLEDGE GAPS RELATED TO THE SOIL MICROBIOME

FAO plays a key role in reviewing the latest scientific research, identifying knowledge gaps and informing policy. In keeping with the aforementioned, the authors of this [review](#) have identified an urgent need for further research and development to help answer important soil microbiome-related questions ([Table 2](#)).

3.2 KEY OPPORTUNITIES AND CHALLENGES

Better understanding of the soil microbiome holds game-changing potential for developing innovative solutions to global problems of food insecurity and malnutrition, environmental degradation and climate change. Microbiome science, technology and innovation has the power to transform multiple aspects of how we manage our planet's natural resources – from obtaining our food to improving the health of people and ecosystems, all within the framework of a sustainable bioeconomy. But what do these innovative solutions look like in the world of crop production?

There are two guiding approaches to soil microbial-based interventions at the moment. It is important to stress that they are complementary, rather than exclusive.

One approach focuses on the choice of **crop production practices** (and their adaptation to local farming systems) designed to foster a multifunctional, healthy soil microbiome. As described in this literature review, certain practices are known to have beneficial effects on the soil microbiome and the functions they provide. Those that stand out are use of organic fertilizers, reduced tillage, increasing on-farm plant diversity, and plant variety selection. So-called nature-based solutions thus aim to restore and maintain ecological balances in the soil by virtue of soil microbial activities.

A second approach centres on **microbial-based inputs**, or agricultural biologicals. These products refer mainly to biopesticides, biofertilizers and other types of biostimulants. The private sector has already invested significantly in this field, with large agrochemical companies being key players. The market for agricultural bio-innovations built on microbiome research is growing rapidly. A 2020 report by Fortune Business Insights has projected this market to expand at a compound annual growth rate of more than 14 percent to reach a value of almost USD 11 billion by 2025. Meanwhile, the microbials segment is anticipated to dominate the agricultural biologicals market, the latter predicted to be valued at almost USD 19 billion by 2025.

Looking beyond agricultural applications, soil microbiome-based innovations can also target multiple planetary challenges to promote ecosystem health. This can best be accomplished through a systems-oriented perspective such as One Health. Currently, there are two approaches: an input-based method; or potential solutions where the entire microbiome is manipulated *in situ*. This latter field of research, which implies a dramatic shift in soil management, could lead to consortia-based microbiome applications that target ecosystem restoration goals. Such applications that are currently being explored include

restoring degraded soils and remediating polluted soils, promoting plant health and growth, increasing carbon storage, reducing greenhouse gas emissions, and contributing to adaptive management strategies in the context of climate change. Bio-sequestration and bioremediation innovations, many of which rely on soil microbiome functions, have been estimated to have a potential economic impact of USD 15–30 billion over the next 10 to 20 years.

Furthermore, there is some evidence suggesting that humans may also benefit directly from exposure to the soil microbiome, the primary examples focusing on the human immune system.

While the applications of (soil) microbiome science seem very promising – be it for the commercial plant production sector or for the provision of wider public goods such as climate change mitigation or human health – there are still quite a few challenges to tackle. They range from technological and scientific issues to market and regulatory needs to public acceptance and ethical questions. Hurdles include:

- ▶ Competitiveness with agrochemical alternatives, meaning that biologicals need to be economically and logistically competitive in terms of price, transportation and storage.
- ▶ Compliance with regulations and standards, including through self-monitoring.
- ▶ Public acceptance, requiring that not only industry and farmers benefit from the innovations, but also civil society and any others concerned by environmental and social impacts. Microbiome engineering will strongly benefit from advances in the field of synthetic biology, which aims to create new biological organisms for specific tasks, but it is equally important to develop safety mechanisms that ensure these organisms can be controlled. Without these controlling mechanisms, public acceptance is likely to be low.

These and other challenges can be partly addressed by policy.

TABLE 2.

THE SOIL MICROBIOME: PRIORITY KNOWLEDGE GAPS IDENTIFIED IN THIS REVIEW

- ▶ How can a better understanding of **soil microbiota diversity and functions** help (i) leverage their enormous potential to design and manage sustainable agroecosystems, and (ii) more broadly, better describe determinants of biodiversity loss, as well as the potential consequences?
- ▶ How could more knowledge about the role of soil microbiota in **biogeochemical cycling** (e.g. of carbon, nitrogen, phosphorus) impact our ability to adapt to and manage climate change? For instance, (i) improved knowledge of soil microbial functions could help improve the accuracy of models seeking to predict outcomes of biogeochemical processes; and (ii) a more precise understanding of these mechanisms could help guide nutrient management strategies, benefiting not only crop production and soil health but also our understanding of greenhouse gas emissions in agroecosystems.
- ▶ In relation to **newly emerging fields of research** where the microbiome appears to play a decisive role, what is the impact of soil protists in nutrient dynamics and soil bacteriophages in antibiotic-resistance gene transmission? And in the plant breeding field, could further attention to so-called missing plant microbes contribute solutions to our global, environmental challenges? How can deep soil microbial ecology help identify strategies to preserve and increase deep soil carbon stocks in agroecosystems? And how do micro- and nanoplastics impact soil microbe-mediated biogeochemical processes and ecological functions, as well as complex trophic relationships?
- ▶ How can soil microbiota be leveraged to directly **engineer improved soil and plant health**? Emerging areas that are attracting attention include microbiome biofortification, the so-called soil immune response, soil remediation and microbe-mediated crop responses to climate stress.
- ▶ How can an improved understanding of the complex relationship between the soil microbiome and **antimicrobial resistance** better inform currently unanswered questions about (i) entry pathways of antibiotic-resistant elements into agricultural soils, potential cross-talk between soil and plant resistomes, and possible health risks posed by consuming treated crops; and (ii) possible selection for pesticide- and plastic-degrading soil microbial species, and the potential impact on antibiotic-resistant genes in the soil? How might better monitoring of antimicrobial quantities used globally by the agricultural sector inform a One Health approach to understanding pathogen resistance?
- ▶ How can we strengthen interdisciplinary collaborations to develop a greater understanding of **interconnections** between ecosystems? One Health offers such an approach, and an appropriate framework to better understand the direct and indirect links between the soil microbiome and human health.

4

POLICY RECOMMENDATIONS

Findings from this review led the authors to recommend that policymakers give adequate space to the critical role the soil microbiome plays in sustainable food production systems and resilient agricultural practices.

The following policy recommendations, based on the current comprehensive review of the relevant scientific literature and complemented by the soil microbiome focus group workshops, take account of the opportunities, challenges and risks related to soil microbiome innovations.

The policy recommendations are grouped under four broad headings related to distinct areas of policy:

- 1 Public support for research, development and innovation;
- 2 Education and communication;
- 3 Commercialization of microbiome innovations, and increasing the demand for microbiome practices, products and services; and
- 4 Regulations.

1 PUBLIC SUPPORT FOR RESEARCH, DEVELOPMENT AND INNOVATION

Public support for research, development and innovation has been the principle policy area to bridge the gap between microbiome science, the private sector and policymakers to date. Policy instruments used are primarily market-based mechanisms such as research grants and the promotion of public–private partnerships, on the one hand, and communication and outreach activities such as the establishment of networks and organization of conferences and workshops with researchers and policymakers at national, regional and international level, on the other. Although there is a growing number of microbiome initiatives and networks, more interaction and collaboration between different disciplines and between private and public sectors could help us further our knowledge of the microbiome across ecosystems.

- ▶ Policy should **channel resources into research on what constitutes a healthy microbiome**. It should **prioritize exploring the causal relations** between microbiomes and humans, plants, and animals throughout their life spans, as well as environmental health. This should be done using **systems-based approaches** such as One Health.
- ▶ Research policy should **help unify or standardize research protocols on how to study the microbiome**, as well as support action in response to calls to establish a biobank for the microbiome bank, similar to the concept of a seed bank. Furthermore, it should **encourage expanding soil microbiome research** from laboratory studies to field conditions that reflect the complex interactions with other living biomass in the soil. In addition, it should promote investigation into the impacts of micro- and nanoplastics on the soil microbiome, and any potential links to other ecosystems such as the human gut microbiome.
- ▶ Policy should **support unification of microbiome knowledge and actions across disciplines and ecosystems**. This could be done by further encouraging national and international interdisciplinary research collaboration linking microbiome research communities such as plant, environmental, animal, marine and human agrochemical alternatives, making sure that the biologicals are economically and logistically competitive in terms of price, transportation and storage. **Quality regulation is also necessary** to ensure efficacy of microbiome products in the field.

2 EDUCATION AND COMMUNICATION

In line with support for microbiome research, development and innovation, policy should support education and capacity building related to the microbiome. The subject of the microbiome may not be new, but our approach and reach need to expand. For example, microbiome training in higher education certainly exists, but more focus on multi- and transdisciplinary approaches would be beneficial to highlight the microbiome connections between ecosystems. Furthermore, there is a need for microbiology literacy in the general population: what is missing in civil society is a tangible understanding of how the microbiome impacts lives on a daily basis, and in the most basic ways. For policymakers, it is crucial to emphasize that microbiome research can provide solutions to many global challenges, while addressing true cost accounting and emphasizing the value of a long-term approach.

- ▶ Policy should **ensure training of the current and future workforce and scientists** to build capacity for the field. This concerns school-aged to adult education, early-career training, as well as university curricula of bachelor, master and postgraduate programmes.
- ▶ Policy should encourage the training of consumers and citizens to **ensure microbiome literacy**. This should include concerted action from all responsible actors, such as the research community, food and healthcare professionals, industry, regulatory opinion leaders, the media and policymakers, to support broad efforts on microbiome literacy. It should also include the message that microbiome research can provide solutions to many global challenges. Promoting microbiome literacy will help individuals grasp the direct relevance of the microbiome to their daily lives.
- ▶ Policy should also **make sure that local communities have the capacity to benefit from microbiome innovations**, including communities in developing countries. Research and industrial infrastructure to develop and provide biological solutions for the agricultural sector should also be developed in rural and coastal areas, to provide employment opportunities, including to rural youth. This could contribute to stopping rural migration and support public acceptance of these new technologies, while improving collaboration with local communities impacted by ecosystem degradation.

3 COMMERCIALIZATION OF MICROBIOME INNOVATIONS, AND INCREASING THE DEMAND FOR MICROBIOME PRACTICES, PRODUCTS AND SERVICES

Existing policy initiatives should further support the commercialization of microbiome innovations and stimulate the demand for microbiome services and products. Most of this work is done by the private sector without government support, albeit limited to those applications that promise high economic returns. This is particularly evident in the pharmaceutical sector, but also increasingly in agriculture. However, public programmes that target private sector initiatives do exist. They usually consist of funds that can be accessed by the private sector through various mechanisms such as grants or loans, which require a process of consideration.

One of the central issues regarding microbiome products for use in agriculture is regulation (see 4 Regulations), as there is currently no robust testing or certification process, despite there being myriad commercial microbiome products on the market. Furthermore, there is no synchronization between regulatory frameworks of countries. Another regulatory need is to address the impact of pesticides on the soil microbiome, as well as other physical soil treatments, even if more research is urgently needed to better describe such effects before they can be translated into policy. This will help develop more appropriate assessments of the impacts of biopesticides, which are currently based on chemical pesticide regulations, despite major differences in the products.

► Policy should particularly **support the development and commercialization of those microbiome applications that are destined for the common good**, such as those targeting carbon sequestration, rehabilitation of degraded or contaminated soil, plant growth promotion, and climate change resilience.

► Policy should furthermore **support the competitiveness of biological applications with agrochemical alternatives**, making sure that the biologicals are economically and logistically competitive in terms of price, transportation and storage. Quality regulation is also necessary to ensure efficacy of microbiome products in the field.

4 REGULATIONS

Regulations and laws in the context of soils are scarce. Only a few countries have specific legislation on soil protection. Soil is often addressed in legislation related to other areas, such as chemical law, waste law and in legislation on facilities and industrial installations. To our knowledge, none of these addresses the soil microbiome. Furthermore, agricultural policies do not venture into the importance of soil microorganisms, let alone the microbiome.

One of the specific needs that stands out is having regulatory tools, or monitoring systems, that take stock of soil quality over time. For instance, the importance of developing robust, reliable and resilient biological indicators for soil quality monitoring has been emphasized in order to establish an early warning system for potential losses of soil multifunctionality. Technical harmonization at the international level would contribute to this need, and others, by enabling the sharing of genetic and functional information related to biodiversity.

Another need to emphasise is transparency and accountability regarding microbiome science, technology and innovation. New biological capabilities come with profound and unique risks that need serious debate, and proactive, rather than reactive, approaches toward mitigation, as experience from the past has shown. The potential impact of such products partly hinges on consumer, societal, and regulatory acceptance.

- ▶ Policymakers should **develop regulatory frameworks** that require evaluation of health and environmental claims of new food or environmental microbiome-based products, legislative proposals that reward sustainable management of agricultural soils and the microbiome, and strategies that recognize the interconnectedness of different ecosystems to develop solutions for restoring soil health and functions. There is also a need for **technical harmonization at the international level** in order to share genetic and functional information related to biodiversity – e.g. the Global Soil Laboratory Network (GLOSOLAN) works on the preparation of globally harmonized standard operating procedures for the assessment of biological and biochemical parameters in soils.
- ▶ **It is important that policymakers, farmers, scientists, industry and citizens are all part of the conversation** when it comes to highlighting the key challenges of new microbiome-based products, and identifying the steps necessary to enable innovation and mitigate risks – the International Network on Soil Biodiversity, established within the framework of the FAO Global Soil Partnership, provides an excellent forum for such discussions.
- ▶ Policymakers need to **allow public scrutiny** of new microbiome technologies and **ensure adequate safety assessment** prior to any introduction, providing guidance on the use and potential misuse of new microbiome-based technologies. While it is important to highlight the opportunities of these applications, it is key that consumers are aware of the associated risks and protected by fit-for-purpose regulations, where necessary.

A TIMELY ENDORSEMENT

This review underscores the critical importance of soil microbial biodiversity and soil health in the provisioning of ecosystem functions and services. It also emphasizes that (microbial) ecosystems are interconnected, and traces the underlying relationship between the microbiome and healthy soils, people and the climate system. The vast and relatively underexplored diversity of soil microbial genes and functions offers exciting opportunities for innovative solutions, which could contribute to achieving the SDGs as well as a sustainable and circular bioeconomy.

During the series of virtual conferences in July 2020, microbiome experts identified FAO as an appropriate intermediary between the scientific community and policymakers worldwide to identify and share innovative ideas and solutions that can bring rapid and tangible change to agrifood systems. From a microbiome science perspective, this entails investing in a dedicated, multidirectional

science–policy interface, the purpose of which would be to identify and prioritize scientific information needed for policymakers and policy priorities for research agendas.

Leaving no one behind is a central narrative in the FAO Strategic Framework 2022–2031. The strategy aims to achieve this vision through sustainable, inclusive and resilient agrifood systems for better production, better nutrition, a better environment and a better life. Emerging soil microbiome-based innovations in cropping systems could play a major role in better production and better environment, both of which advocate for biodiversity in agricultural systems.

The soil microbiome plays a pivotal role in supporting biodiversity, ecosystem and human health, and climate change mitigation and adaptation. This review offers a timely endorsement of this important message.

NOTES

1. **International Advisory Council on Global Bioeconomy.** 2020. Expanding the Sustainable Bioeconomy – Vision and Way Forward. Communiqué of the Global Bioeconomy Summit 2020. Berlin. Cited 27 June 2022. https://gbs2020.net/wp-content/uploads/2020/11/GBS2020_IACGB-Communique.pdf#page=14
2. **Berg, G., Rybakova, D., Fischer, D., Cernava, T., Vergès, M.-C.C., Charles, T., Chen, X. et al.** 2020. Microbiome definition re-visited: old concepts and new challenges. *Microbiome*, 8(1): 103.

FAO's role is to
bridge science with policy
to bring forward beneficial
microbiome innovations.



The comprehensive review on the soil microbiome and crop production practices, upon which this executive summary was based, provides important clues as to how we might reduce climatic and environmental impacts of our agrifood production systems. The review makes clear that the soil microbiome plays a pivotal role in ecosystem health, agroecosystems and the climate system.

This executive summary for policymakers and researchers outlines key opportunities and challenges regarding microbiome-based, innovative solutions for global problems. Framed within concepts of sustainable bioeconomy and One Health, it highlights how systemic,

cross-disciplinary and cross-sectoral approaches are critical to realising the potential of microbiome science, technology and innovation, as well as mitigating risks associated with this fast-developing field.

This summary is based on *A review of the impacts of crop production on the soil microbiome: Innovations and policy recommendations to address environmental degradation, climate change and human health*, produced by the FAO microbiome working group. The review is among the first of several FAO publications that will address different microbiome ecosystems and their relatively underexplored potential to alleviate global problems.

FOR MORE INFORMATION SEE:

Office of Climate Change, Biodiversity and Environment

Bioeconomy@fao.org

www.fao.org/in-action/sustainable-and-circular-bioeconomy

Food and Agriculture Organization of the United Nations
Rome, Italy