MICROBIOLOGY SOCIETY

A Sustainable Future

Achieving Soil Health: Opportunities and Challenges for Microbiology Research and Innovation

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Foreword

Step by step and year after year, the health, wealth, and well-being of the global population is improving. Not on every single measure every single day, but as a rule. However, many challenges remain. Extreme weather events, biodiversity loss and forced displacement are affecting tens of millions of people worldwide every year. These catastrophic events generate headlines and grab our attention in ways that progressive improvements rarely do. When things get better, such as the decrease in child mortality across the world, it is because lots of people are working together on the frontlines every day, over the long term, to bring about the changes that constitute progress. Through the discovery of antibiotics and vaccines, water sanitation and hygiene, bioremediation and food security, to name but a few contributions, microbiology's impact has been profound.

The United Nations, 17 Sustainable Development Goals, including 'good health and well-being', 'gender equality' and 'affordable and clean energy', build on the success of the Millennium Development Goals to close the gap and cement hundreds of years of incremental human progress with the support of a strong international community. The Global Goals are a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030.

Microbiology is essential to achieving the Sustainable Development Goals. The ocean and soil microbiomes, for instance, act as natural carbon sinks and could be used to further sequester carbon and mitigate the effects of anthropogenic climate change. Microbial technology can be used to produce sustainable clean energy in the form of biofuels. Microbial secondary metabolites could provide novel antimicrobials to tackle the pressing issue of antimicrobial resistance. Many of the steps that will be taken on the long road towards achieving the Sustainable Development Goals will involve microbial processes. The major policy decisions needed to set us on this journey require knowledge of relevant microbial activities and how these can be channelled for the greater benefit.

Microbiology has made our present better than our past, and can make our future better still. Policy decisions based on knowledge of underlying microbiological processes will be the basis of future progress, well-being and, ultimately, sustainability. With this project we hope to share our excitement for the profoundly positive effects that microbes have on human beings, the biological world and the entire planet and its atmosphere. Microbiologists, policymakers and others must work together to propel us towards the global goal: a sustainable future.

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1. Executive summary

The year 2020 has shown the need for societies to transition into ones that are better connected, inclusive, resilient and, importantly, more sustainable. Sustainability encompasses the environment, economy and health, which present as interlinked global challenges in which microbiology features prominently. The Microbiology Society embarked on its A Sustainable Future project, recognising the potential of the microbiology research community in the UK and Republic of Ireland to tackle these challenges, by identifying three specific areas, antimicrobial resistance, the circular economy and soil health, that address many of the 17 United Nations Sustainable Development Goals (UN SDGs). A sustainable future depends critically on healthy, sustainably used ecosystems that support a growing human population and our economies without compromising the ability of future generations to meet their own needs.

Five of the 17 SDGs are addressed by achieving and maintaining soil health, for which microbiology can offer many opportunities as well as challenges. Microbes are essential for food security, e.g. through improving crop productivity and sustainable agriculture (SDG 2; no hunger); water quality and soil quality, e.g. through pollution bioremediation, the promotion of soil formation and the prevention of soil erosion (UN SDGs 6 – clean water and sanitisation – and 15 – life on land); climate control, e.g. through soil carbon sequestration and reduction of greenhouse gas emissions (UN SDG 13; climate action); and human health, e.g. via improved control of pollutants, pathogens and nutrients (UN SDG 3 – good health and well-being – as well as SDGs 2 and 6). Restoring and maintaining soil health is not only relevant to agriculture, but rural and urban societies alike will benefit as better quality land becomes available for use, while natural environments will benefit from improvements in (microbial) biodiversity.

The need to interact and collaborate more efficiently in order to achieve progress and impact is one of the key results of discussing soil health with microbiologists and others active in associated disciplines and sectors, including researchers, farmers and industry, and governmental, regulatory and societal organisations. Collaborative efforts resulting in the creation and adoption of evidence-based soil health policies will be crucial for achieving a sustainable future for generations to come.

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2. Recommendations

Microbiology research in soil health

1. Sustained microbiology research and innovation in the field of soil health is imperative to help deliver the SDGs, particularly goals related to hunger (SDG 2), good health and well-being (SDG 3), clean water and sanitation (SDG 6), climate action (SDG 13) and life on land (SDG 15).

Framing soil health

2. The soil health community should evolve the concept of soil health towards a universal definition that is understood and adopted by all stakeholders, with metrics that encapsulate a soil's physical, chemical and biological features, but also takes the soil's specific ecosystem into consideration.

3. The soil health community should ensure that research is accessible to non-academics by raising awareness amongst stakeholders and society, which should include activities such as showcasing work in non-academic outlets and improving outreach in schools and (agricultural) colleges.

Enabling a collaborative community

4. Funders and the soil health community should work together to develop a coherent long-term funding strategy with interdisciplinary collaboration at its heart to ensure the continuity of research and monitoring over larger (time) scales that are relevant to soils.

5. Funders and the soil health community should support the creation of a soil health innovation and knowledge centre that pulls together capabilities from different disciplines and sector organisations to foster collaboration and should provide opportunities for (re)training and development of skills and competencies for a next-generation sector workforce that can confidently and rapidly accelerate the soil health agenda.

Collaborating with industry

6. The soil health academic community should increase engagement and collaboration with agriculture and industry in order to improve knowledge exchange for effective translation of research outputs into farm-ready affordable innovations, while also developing policy and quality control mechanisms to incentivise sustainable soil management.

Transferring knowledge and skills

7. Funders and the soil health community should support increased education and (re)training of soil health researchers, advisors and sector employees to address a lack in capacity, and should ensure that sector-wide knowledge, skills and competencies are available for successful participation in interdisciplinary projects. The Microbiology Society should align with other societies to help facilitate progress in this area.

3. Soil health and the Sustainable Development Goals

> Soils are critically important to the functioning and sustainability of the planet. They provide a range of essential functions, including producing the vast majority of our food, filtering our water and regulating our climate. Most of these functions are underpinned by the micro-organisms, making the knowledge of how they work of vital importance."
> *Dr Fiona Brennan, Irish Agriculture and Food Development Authority*

The quality of soil and its suitability for growing crops have been important since humans developed agriculture. In 1888, *Rhizobium* spp. were found living in the roots of leguminous plants, suggesting the importance of soil microbes. It is now known that soil microbiomes are diverse communities with complex interactions, made up of a vast array of bacteria, fungi, archaea, protists and viruses, the composition of which is crucial for carbon and nutrient cycling, plant health, water retention, and even soil structure [1].

Food production depends on croplands and water supply, which are under strain as human populations increase. Microbiology plays a key role in securing a future in which healthy and sustainable soils can effectively support agriculture and food security, while preserving our limited land and freshwater resources.

In 2015 the United Nations (UN) adopted the Sustainable Development Goals (SDGs), a collection of 17 goals and 169 associated targets. Wide-ranging and ambitious, the goals are a blueprint for transforming our world by 2030. They are interconnected and address economic, social and environmental challenges crucial to a better and more sustainable future for all. (More information on the UN SDG framework is available in Appendix 1)

Whilst there is no specific goal, target or indicator in the SDG framework to ensure soil health, it is recognised that this is essential for the achievement of many of the SDGs, and the SDG indicators indirectly cover many aspects of soil health.

Microbiology can help to achieve the SDGs by exploring new possibilities for the restoration and promotion of healthy microbial populations in the soil.

- Microbiology can provide insight into the effects of intensive agricultural methods such as tilling and excessive fertiliser application on soil microbiomes, leading towards farming methods that improve soil health, supporting sustainable agriculture that is able to feed a growing population (SDG 2).
- Novel microbiological innovations can be used, such as methods that use microbes to remove soil contaminants, making more land available for recreation, housing and agriculture, while improving clean water availability (SDGs 3 and 6).
- Soil micro-organisms can be harnessed to draw carbon out of the atmosphere and sequester it in the soil, thereby providing a significant means of reducing atmospheric greenhouse gases. Understanding and controlling the availability and concentrations of microbes in soil will be important for combating climate change and ensuring stable ecosystems (SDGs 13 and 15).

[1] **Microbiology Society.** *Soil health explainer.* https://microbiologysociety.org/uploads/assets/f0266831-5df8-438a-bc2bebdd22de9f5f/Soil-Health-Explainer.pdf

SDG 2: No Hunger: soil microbiomes are an important component of many processes that influence soil fertility, including nitrogen and phosphate cycling, and may help to reduce the reliance on artificial fertilisers and promote the sustainable intensification of agriculture.

SDG 3: Good Health and Well-being: contaminants in polluted soils often affect human and environmental health and well-being negatively. Bioremediation removes contaminants in an efficient manner by adding microbes to the soil or promoting the growth of those already present.

SDG 6: Clean Water and Sanitation: bacteria and fungi influence the physical structure of soil, affecting water resource availability, and may mitigate flood and soil erosion. Wastewater sludge is often applied to soils, both to increase soil fertility and as a method of disposal. However, soils can also be polluted with pathogens and hazardous compounds present in insufficiently treated wastewater sludge.

SDG 13: Climate Action: microbial activity is essential for the decomposition of organic matter and for carbon storage, which in turn influences atmospheric CO^2 levels. Microbes are also involved in the cycling of important nutrients in soil, such as phosphorous and nitrogen, activities that contribute to climate change in the form of potent greenhouse gases.

SDG 15: Life on Land: microbes can help halt biodiversity loss through increased nutrient availability and the breakdown of organic matter, which allow other organisms to prosper. Microbial components also form a large part of diversity in the soil and should be considered when assessing and conserving soil biodiversity.

4. Soil health research spotlight

Microbiologists working in the field of soil health have the potential to help progress the UN SDGs, particularly goals related to hunger (SDG 2), good health and well-being (SDG 3), clean water and sanitation (SDG 6), climate action (SDG 13) and life on land (SDG 15).

4.1. Micro-organisms as indicators of soil health

With an estimated 40,000 to 50,000 species of micro-organisms per gram of soil, soils represent one of the most highly diverse ecosystems on our planet [1]. Soil microbiomes are key players for the restoration and conservation of soil health and for achieving SDGs 2, 6, 13 and 15.

While progress is being made, there is currently no generally accepted definition of, or metric for, a 'healthy' soil microbiome. A microbiome or soil that is considered healthy for one crop may not be healthy for another. The soil is a hugely complex environment that varies temporally and spatially, and the additional complexity of soil types means that categorisation and transferability of bioindicator metrics are challenging [2]. The lack of causal links between taxonomic diversity and ecosystem functions also makes describing a healthy soil microbiome difficult, as many of the biological pathways are either redundant, or not yet understood. Many molecules identified in soils have no known function, while the taxa that produce these compounds remain elusive.

Recent advances in DNA sequencing technology have enabled microbiologists to start characterising the diversity of soil microbiomes, which is increasing our understanding of the roles microbes perform in soils and may help to improve management of soils. Exciting research in this area includes the use of high-throughput metagenomic sequencing on soil samples to assess the abundance of species in the soil and the integration of high-throughput sequencing with methods such as mass spectrometry and machine learning to better understand microbial function in the soil [3].

There is now an opportunity for microbiologists to develop and identify precise and actionable microbial indices for soil health metrics of interest that are suitable for adoption across many soil types and can be easily interpreted in specific soil contexts.

[1] **Microbiology Society.** *Soil health explainer.* https://microbiologysociety.org/uploads/assets/f0266831-5df8-438a-bc2bebdd22de9f5f/Soil-Health-Explainer.pdf
[2] Michael Schloter, Paolo Nannipieri, Søren J. Sørensen, Jan Dirk van Elsas, Microbial indicators for soil quality, *Biology and Fertility of Soils*, 2018, 54, https://doi.org/10.1007/s00374-017-1248-3
[3] Susana I. C. J. Palma, Ana P. Traguedo, Ana R. Porteira, Maria J. Frias, Hugo Gamboa, Ana C. A. Roque, Machine learning for the meta-analyses of microbial pathogens' volatile signatures, *Scientific Reports*, 2018, 8, https://doi.org/10.1038/s41598-018-21544-1

U-GRASS: microbial indicators for soil sustainability – Dr Robert Griffiths (UK Centre for Ecology and Hydrology)

As part of the Natural Environment Research Council (NERC)-funded Soil Security Programme, the U-GRASS project questioned how soil microbial communities and the functions they provide are affected by land management. They surveyed a range of land management contrasts across he UK using molecular and functional measurements and found that across similar soil types, the same microbes responded strongly to management, irrespective of geographical location. However, when looking across different soil types under different climatic and geological conditions, they found that different organisms responded to management and they could therefore define certain microbial taxa as ecosystem 'indicator' taxa, as is typically done for larger organisms for monitoring terrestrial or aquatic ecosystem health.

To help translate to farmers and policymakers what change in these microbial indicators means for services such as crop yield and soil processes, the team examined soil microbial function. Interestingly, they found that certain functional genes were highly dependent on soil conditions, whilst others and particularly those involved in nitrogen cycling were strongly altered by land management, likely due to fertiliser use. However, key challenges remain in terms of linking change in microbial taxonomic indicators to specific gene functions, to build an ecologically grounded mechanistic understanding of soil biochemical processes. Such advances could benefit the development of new agricultural practices, which are less reliant on application of industrially produced fertilisers.

Find out more about the U-GRASS project here**: https://soilsecurity.org/u-grass/**.

4.2. Sustainable food production

2 ZERO HUNGER

3 GOOD HEALTH AND WELL-BEING

6 CLEAN WATER AND SANITATION

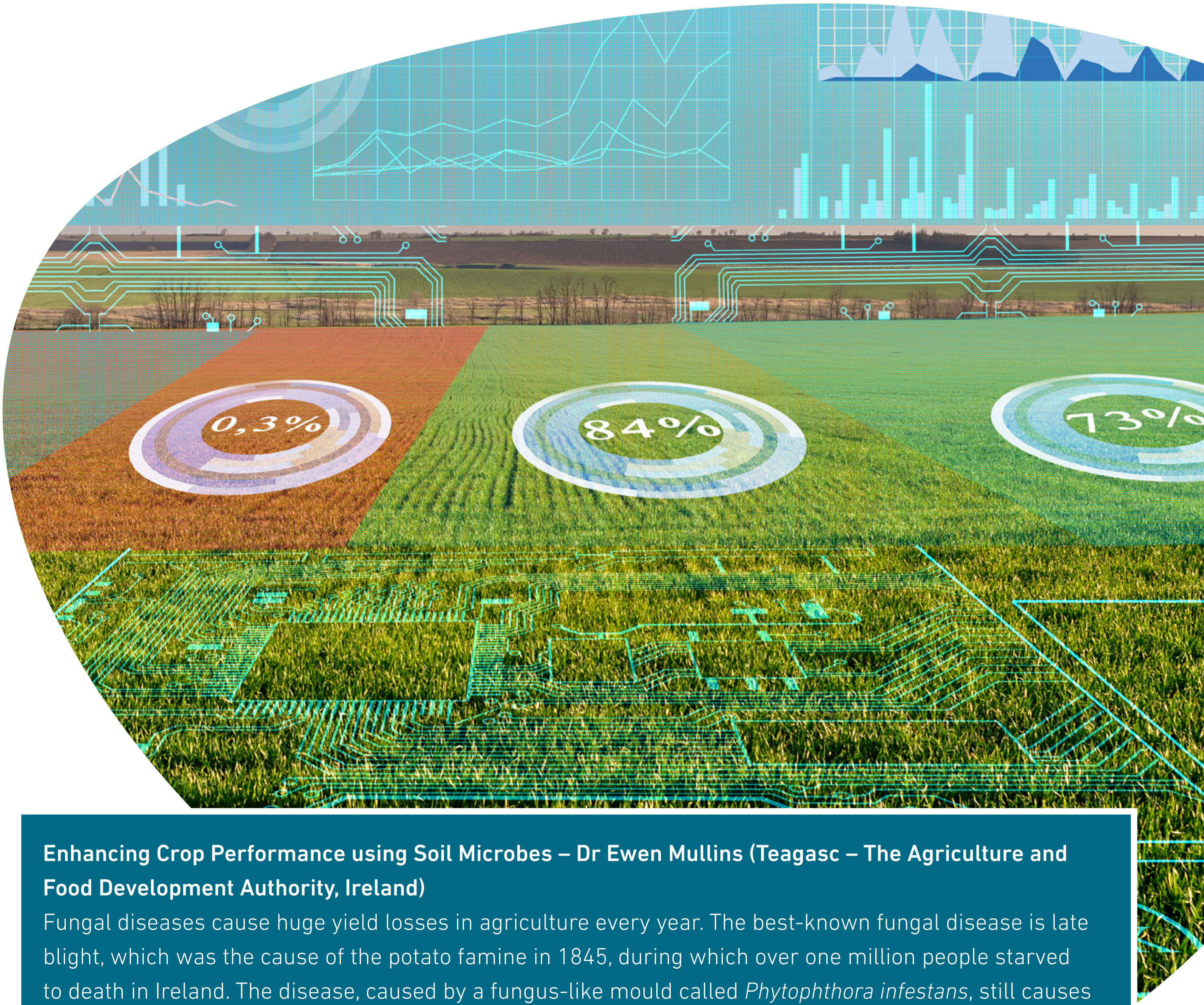
Micro-organisms play a key role in securing a sustainable future in which healthy soils can effectively support agriculture, food security and healthy populations (SDGs 2, 3 and 6). Fertile soils have abundant microbiomes and micro-organisms can be harnessed to provide sustainable food chains by enhancing crop production, improving nutrient absorption and plant growth, increasing disease resistance and helping stabilise soil structure.

Although farming practices such as intensive tilling and fertilisation of arable soils reduce soil microbiome diversity and soil biomass, micro-organisms also hold solutions to issues that threaten healthy soils. Microbial solutions that have the potential to sustain intensification of agriculture include:

- Harnessing microbiology to sustainably increase the availability of nitrogen and phosphate. Nutrient availability is vital for producing crops, and currently many farmers rely on synthetic fertilisers to increase nutrients such as phosphorus and nitrogen to improve yields. Nitrogen-fixing and phosphate-solubilising microbes can play a crucial role in increasing the availability of nitrogen and phosphate. Advances in our understanding of microbial nitrogen fixation and phosphate solubilisation promise to provide solutions for a sustainable high-yield agriculture [4].

- Inoculating plant-soil microbiomes with beneficial microbes to promote plant health and growth, control pathogens and provide protection against environmental stresses. Healthy and diverse soil microbiomes are crucial for plant health and can help to protect plants from soilborne pathogens, thereby halting a potential loss of biodiversity. For example, microbiologists are developing bioinoculants that take advantage of beneficial microbes sourced from the rhizosphere, in order to promote plant health and enhance crop yields. Endophytic root microbiomes have recently been identified for their ability to consistently suppress fungal root disease in a specialised metabolism-dependent manner [5].

[4] **Microbiology Society.** *Harnessing natural bio factories against deadly soil fungal pathogens of potato seed tubers: bacillus subtilis, Dr Touseef Hussain, https://microbiologysociety.org/our-work/75th-anniversary-a-sustainable-future/soil-health/soil-health-case-studies/harnessing-natural-bio-factories.html*
[5] Víctor J. Carrión, Juan Perez-Jaramillo, Viviane Cordovez, *et al.*, Pathogen-induced activation of disease-suppressive functions in the endophytic root microbiome, *Science*, 2019, 8: https://doi.org/10.1038/s41598-018-21544-1



Enhancing Crop Performance using Soil Microbes – Dr Ewen Mullins (Teagasc – The Agriculture and Food Development Authority, Ireland)

Fungal diseases cause huge yield losses in agriculture every year. The best-known fungal disease is late blight, which was the cause of the potato famine in 1845, during which over one million people starved to death in Ireland. The disease, caused by a fungus-like mould called *Phytophthora infestans*, still causes major losses in global food production, and in order to manage the disease, farmers must use multiple applications of chemical fungicides on their crops, with over 10 applications per year.

Agrobacterium tumefaciens, sometimes referred to as 'the world's plant engineer', has previously been harnessed for many years to generate genetically modified crops, but limitations to its use include patents and technical challenges. To overcome this, researchers at The Agriculture and Food Development Authority (TEAGASC) have identified a novel bacterium, which can modify plant characteristics and provide beneficial traits, such as resistance to disease. This alternative bacterium, called *Ensifer adherens*, is collected from the rhizosphere – the diverse microbial community that lives in the soil around plant roots. *Ensifer adherens* can be used to change the genetic material of the plant by a process called *Ensifer*-mediated transformation (EMT), whereby the plant genome is engineered by the bacteria, and characteristics are modified. The team have already demonstrated the potential of EMT to generate potato varieties with late blight resistance. It is hoped that introducing novel genetic resistance such as this to crops will reduce the need for fungicides in agriculture, which is vital in the shift to a more sustainable farming system, while also reducing pollution of soils and waterways.

4.3. Preserving biodiversity and combating climate change

3 GOOD HEALTH AND WELL-BEING

6 CLEAN WATER AND SANITATION

13 CLIMATE ACTION

15 LIFE ON LAND

Soils are one of the most biodiverse habitats on Earth, but microbial communities are under threat due to anthropogenic influences. There are considerable concerns about the number of viable growing cycles remaining in global soil stock, which will precipitate microbial habitat and diversity loss, and may be a barrier to achieving SDGs related to the environment (SDGs 3, 6, 13 and 15).

However, micro-organisms are crucial allies to protect soil, water and air quality. They can provide key ecosystem services to halt biodiversity loss and combat climate change through microbial processes including:

- Bioremediation of waste and pollutants: bioremediation is a process whereby micro-organisms, including bacteria and fungi, convert contaminants in the soil into less hazardous substances, and sometimes even use them as a food source, thereby leading to degradation or removal of the contaminants.
  Microbes can also sequester pollutants such as heavy metals by biosorbing the contaminant to extracellular polymeric substances (EPS) on their outer surfaces. This can help to restore healthy soils and preserve biodiversity by cleaning up pollutants or by reducing leaching or mobilisation. For example, bioaugmentation and biostimulation with macro- and micro-nutrients that limit microbial growth have a positive effect on crude oil degradation by microbes [6].

- Stabilising soil structure and preventing soil erosion and flooding: micro-organisms are important contributors to the maintenance of soil structure by producing sticky compounds that allow soil to form aggregates. For example, microbial EPS, especially EPS protein, improved the aggregate stability of agricultural soils. Filamentous microbes also produce long hyphae that help soil to retain its structure. Soils that are rich in micro-organisms can improve soil structure, leading to an increase in water holding capacity, resulting in less erosion and flooding prevention [7, 8].

- Carbon storage and regulation of greenhouse gases: soil microbiomes influence nutrient cycles such as nitrogen and phosphorous. Micro-organisms can reduce CO^2 emissions by consuming methane in soils and by transforming nitrogen-containing greenhouse gases via denitrification. There is also growing evidence that fungi in soil can be harnessed to draw carbon out of the atmosphere to sequester it in soil, which could be an important solution to climate change [9].

[6] Obioma K. Mejeha, Ian M. Head, Angela Sherry, et al., The impact of Ni on crude oil biodegradation, Chemosphere, Volume 237, 2019, https://doi.org/10.1016/j.chemosphere.2019.124545.
[7] Ohana Y.A. Costa, Jos M. Raaijmakers, Eiko E. Kuramae, Microbial extracellular polymeric substances: ecological function and impact on soil aggregation, *Frontiers in Microbiology*, 2018, 9, https://doi.org/10.3389/fmicb.2018.01636
[8] M. Redmile-Gordon, A.S. Gregory, R.P. White, C.W. Watts, Soil organic carbon, extracellular polymeric substances (EPS), and soil structural stability as affected by previous and current land-use, *Geoderma*, 2020, 363, https://doi.org/10.1016/j.geoderma.2019.114143
[9] Himangshu Dutta, Angshu Dutta, The microbial aspect of climate change, *Energy, Ecology and Environment*, 2016, 1, https://doi.org/10.1007/s40974-016-0034-7

Understanding soil carbon storage in tropical forests – Dr Emma Sayer (Lancaster University)

Tropical forests are globally important stores of carbon, taking up vast amounts of atmospheric carbon dioxide (CO^{2}) and incorporating carbon into plant biomass and soils. Estimates of tropical forest carbon sequestration show that rising elevated atmospheric CO^{2} levels appear to have boosted forest productivity, which in turn has helped offset anthropogenic CO^{2} emissions. However, although forest soils worldwide contain more carbon than the atmosphere, we still know very little about how carbon is stored in the soil, particularly in the tropics, and it is not clear whether increased plant growth will also result in greater incorporation of carbon belowground.

To assess the impact of increased forest growth on soil carbon dynamics, Dr Emma Sayer and her team embarked on a 5-year experiment funded by a European Research Council Starting Grant. The team investigated microbial decomposition of plant litter and soil organic matter in a unique experiment in a tropical forest in Panama, in which litter was added or removed monthly from large experimental plots since 2003. This long-term experiment allowed them to measure changes in soil processes and evaluate soil carbon stocks in response to more than a decade of litter removal or double litter inputs. Their findings demonstrate that increased forest productivity will not necessarily enhance soil carbon sequestration. Instead, we need to better understand how plant litter, microbial activity and soil chemistry interact to stabilise organic matter in the soil to mitigate the impact of climate change.

Recommendation 1:

Sustained microbiology research and innovation in the field of soil health are imperative to help deliver the SDGs, particularly goals related to hunger (SDG 2), good health and well-being (SDG 3), clean water and sanitation (SDG 6), climate action (SDG 13) and life on land (SDG 15).

OPINION PIECE

Dr Mark Pawlett and Dr Jacqueline Hannam (Cranfield University)

Soil health or soil quality?

Describing the health of complex systems requires the inclusion of interactions, both within the system and interactions with its environment. Definitions of human health incorporate quality of life, physical, mental and social well-being, and the absence of disease (World Health Organisation). For soils, the term 'soil quality' [10] has largely been replaced by 'soil health'; yet, these terms are often used interchangeably without clear context or definition. The main difference in definitions is that 'soil quality' typically uses indicators of soil condition for specific individual traits or functions (such as yield), similar to a 'quality of life' indicator. In contrast, 'soil health' encompasses benefits to wider ecosystem services within a more holistic approach, and as such considers multiple functions and their interactions in an ecological context. Many use variants of Doran's [11] definition, which describes soil health as 'the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health'; thereby including multiple ecosystem functional traits, or 'services' in addition to yield. Soil health is now a major environmental criterion for the sustainable management of soils used by policymakers in the UK. Providing greater clarity on definition is important, given that the term tries to explain complex environmental systems and interactions to different stakeholders with different perspectives relating to sustainable land and environmental management.

What do soils do?

Soil functions are intrinsically dynamic processes, many of which necessitate biological interactions that are sensitive to management strategies. Functional traits include food crop production, carbon transformation and regulation processes, nutrient cycling processes, soil structure and stability, biodiversity and biological population regulation (soil food webs), soil water fluxes, and regulation of soil and water pollutants. A healthy soil encompassing multiple functional trails is required for a healthy ecosystem, and subsequently the delivery of ecosystem services and goods required by society. Healthy soils are biodiverse and resilient to perturbation, with efficient energy and nutrient flows that are often unique to ecosystems. Complexity, natural variability and ecosystem boundaries can also change due to multiple anthropogenic stresses and disturbances (e.g. climate shocks and weather extremes). Definitions thus need to consider ecosystem complexity, whilst also reflecting emergent soil properties and adaptability in changing systems. As boundaries shift, management practices to maintain specific ecosystem services may not be sustainable or suitable.

Towards the definition and measurement of soil health

Soil health can be defined as the capacity of soils to deliver multiple functional traits that are required to maintain ecosystem stability while allowing ecosystem development in a changing environment. Functional traits of specific ecosystems that are valued by society will vary between ecosystem and land use types.

[10] Karlen D.L. et al., Soil quality: A concept, definition, and framework for evaluation. *Soil Science Society of America*, 1997, 61, https://doi.org/10.2136/sssaj1997.03615995006100010001x
[11] John W. Doran, Soil health and global sustainability: translating science into practice, *Agriculture Ecosystems & Environment*, 2002, 88, https://doi.org/10.1016/S0167-8809(01)00246-8
[12] Else K. Bünemann, Giulia Bongiorno, Zhanguo Bai, Soil quality-A critical review, *Soil Biology Biochemistry*, 2018, 210: https://doi.org/10.1016/j.soilbio.2018.01.030

Redefining soil health

Not all soil functional traits can be delivered simultaneously; for example, the simultaneous provision of food crops and water storage is difficult. Assessments of soil health should thus consider multiple functional traits that are deliverable by the identified ecosystem type. The majority of commercially available soil health assessments focus solely on crop production (single functional trait: soil quality). Soil physical, chemical and biological parameters should also be represented to support improved decision-making. In particular, the soil biological component is nearly always inadequately represented or absent in many approaches or soil management tools. There is thus a need to better link specific soil characteristics with function to develop a more holistic approach to measuring soil health. Various soil health scorecard systems are currently under development, which attempt to combine multiple parameters. However, a knowledge gap in devising ecosystem-specific indices and scorecard systems that effectively describe either soil quality and/or soil health still remains. For these scorecard approaches to be applicable for practitioners, long-term field trials are required to provide the necessary data to identify the most effective indicators [12].

Monitoring soil health

The soil health parameters measured should reflect soil functions, be sensitive to changes in land management, and be measurable within reasonable time and resource constraints. The evidence suggests that farmers often favour the term soil health as it incorporates in-field assessments that often includes expert qualitative judgements (e.g. visual soil assessment, earthworm counts, soil depth, infiltration rates) combined with quantitative descriptors (organic matter, pH, bioavailable nutrients, microbial biomass). This is fundamentally important as farmers embed valuable local experiential knowledge of their particular soil types into their land management practices. Describing healthy soil thus enables the land manager to engage with their soils, and to view soil as not only existing to support primary production (yield), but also to underpin multiple ecosystem services (functions). Better farmer engagement and co-production of soil health assessments will also facilitate longer-term in-depth analysis of soils. This improves understanding of changes related to natural and anthropogenic disturbance, and the benefits of farming innovations and risk prevention. Defining the critical triggers or 'thresholds' whereby soil becomes either 'healthy' (or not) remains a contested space within both academia and industry.

5. Moving forward in addressing soil health

There is an opportunity to unlock the potential of microbiology to address issues relevant to soil health and therefore help to achieve the SDGs. In order to explore the challenges and opportunities for microbiology in the field of soil health, the Microbiology Society held a series of online workshops, which collectively brought together UK- and Republic of Ireland-based soil health researchers from different fields, along with representatives from industry, funders and government agencies. In this section, we discuss the workshop's view on soil health, identifying the most pertinent opportunities and challenges for microbiology, what more could be done in the UK and the Republic of Ireland if there were fewer barriers, and the interventions needed to achieve a sustainable future.

5.1 Framing soil health

The versatility of the concept of soil health is both an opportunity for wide-ranging adoption as well as a risk for miscommunication between its many stakeholders. There is a need for clarification and agreement around the metrics and indicators that define a healthy soil. As a most complex heterogeneous system with spatially and temporally varying microbiomes, it is important to develop universal functional microbial indices that are precise and actionable, and are adaptable to most, if not all, soil types. Newly identified indices can also be used for unambiguous engagement with land users, as they ought to be easily interpreted in specific soil contexts.

We need to ensure that research is accessible outside of the academic community by publishing work in formats other than purely academic papers. Communications directed at community and stakeholder engagement not only foster a better understanding of microbial indices for soil health, but can also be used to develop a more realistic outlook on long-term monitoring and interventions in soil management in real-world settings.

Extending communications by improving networks of environmental microbiology outreach in schools is likely to have a long-term impact on the diversity and number of people choosing to study and work in this area, and appreciating the importance of micro-organisms.

The press and society at large are aware of global challenges focusing on decarbonising air and food production, and food security. We therefore need to frame soil health better within these global challenges, thereby highlighting the importance of soil research, including the role of microbiologists in communicating and raising awareness of soil microbiology.

Recommendation 2:
The soil health community should evolve the concept of soil health towards a universal definition that is understood and adopted by all stakeholders, with metrics that encapsulate a soil's physical, chemical and biological features but, also takes the soil's specific ecosystem into consideration.

Recommendation 3:
The soil health community should ensure that research is accessible to non-academics by raising awareness amongst stakeholders and society, which should include activities such as showcasing work in non-academic outlets and improving outreach in schools and (agricultural) colleges.

5.2 Enabling a collaborative community

Academic researchers studying soils and soil health are from wide-ranging disciplines covering (agro)economics, soil, plant and (micro)biological sciences, hydrology, ecology, chemistry, physics, engineering and data science. Likewise, non-academic stakeholders and sectors with interests in soils and their functions include agriculture and industry, sport and exercise, culture and recreation, health, policy, landowners and society at large. The innate interdisciplinarity of soil health should therefore be discussed as broadly as possible, ideally from an ecosystem-functioning perspective. At the same time, communication should also be such that the meaning of soil health and its developing metrics and indices are sufficiently clear for all of the associated disciplines and stakeholder sectors.

Soils often adapt slowly upon the introduction of intervention and management techniques derived from novel scientific insights. The existing paradigm of funding for research and innovation contributes to a lack of consistency in funding for soil science that generates knowledge gaps and reduces the understanding of the long-term effects of soil adaptation. Soil microbiology and soil science research would therefore benefit from long-term financial support to allow relevant data collection and analysis to support effective long-term soil management interventions in order to achieve healthy soils. Therefore the soil health community and funding bodies should work together to establish a cohesive long-term plan for a sustained commitment to large-scale, longer-term soil health research projects, with interdisciplinary cooperation at its centre to ensure substantial continuity of soil-relevant research and monitoring over longer (time) scales.

Similarly, professional and learned societies that typically serve one field should also strengthen efforts for its members from a wide variety of disciplines to get together in joint meetings for more efficient communication. Examples of effective integration between disciplines could be showcased by the Microbiology Society at events to advocate more strongly for microbiology in soil science, and to spark interest in cross-disciplinary projects.

In addition, the workshop identified a need to educate and (re)train the next generation of inter- and cross-disciplinary sector workers. Increased training is especially needed in this area in Ireland to resolve the lack of capacity that prevents researchers from responding to calls for funding in the field of soil health. It is therefore recommended that collaborative efforts be made by the education sector, research funding bodies and learned societies to ensure that soil health researchers and sector workers develop the expertise, skills and competencies required to contribute effectively to interdisciplinary projects. The Microbiology Society could advocate for and facilitate cross-disciplinary training of soil scientists and encourage ecologists and agronomists to learn more about soil microbiology, and vice versa.

Recommendation 4:
Funders and the soil health community should work together to develop a coherent long-term funding strategy with interdisciplinary collaboration at its heart to ensure the continuity of research and monitoring over longer (time) scales that are relevant to soils.

Recommendation 5:
Funders and the soil health community should support the creation of a soil health innovation and knowledge centre that pulls together capabilities from different disciplines and sector organisations to foster collaboration and should provide opportunities for (re)training and development of skills and competencies for a next-generation sector workforce that can confidently and rapidly accelerate the soil health agenda.

Microbiology as part of interdisciplinary soil science – Professor Paul Hallett (Chair in School of Biological Sciences, University of Aberdeen)

Over the past 20 years, the most exciting discoveries in soil science have been dominated by microbiologists. New technologies and the interaction between classical 'soil biologists' and more fundamental microbiologists allowed for previously intangible hypotheses to be tested. This thrust of new activity has changed the landscape of soil science. Whilst extremely expensive, state-of-the-art technology has been deployed to study soil biology, the accompanying study of other soil properties sometimes lacks rigour. There are a number of excellent examples of interdisciplinarity in soil science that can be drawn on as a guide to enable future interaction.

The DFG in Germany developed 'Priority Programmes' in which interdisciplinarity is essential to obtain funding. Soil science projects include 'MAD soil – microaggregates: formation and turnover of the structural building blocks of soils' and 'Rhizosphere spatiotemporal organisation – a key to rhizosphere functions'. They have common central experiments, are strongly interdisciplinary and draw on key specialist facilities across Germany.

In the UK, UKRI funded the Soil Security Programme. The seven main projects all had some level of interdisciplinarity, but six focused on soil microbiology and none considered socioeconomic drivers. Most of the projects were thought up and funded independently, limiting cross-over of research activities. By establishing a cluster of projects, the investigators were regularly brought together, so a number of more interdisciplinary projects have emerged.

There is a strong need and desire for more interdisciplinary research involving microbiology and soil science. Hurdles include funding mechanisms, but as demonstrated by DFG Priority Programmes and targeted research programmes from UKRI, these are feasible to address. Centralised longer-term field experiments are essential to allow investigators from a range of disciplines to explore the same system. Better engagement between disciplines and greater training of specialists in soil science would help bring about more interdisciplinary, cutting-edge and meaningful research.

5.3 Collaborating with industry

Information and realistic, actionable metrics for achieving and maintaining healthy soils over the longer term can be advanced by enhancing interdisciplinary communication and collaboration. However, further support for the implementation and maintenance of sustainable soil management will be needed for the agricultural sector and landowners, especially if there is no immediate economic incentive for changing soil management. To implement, promote and/or reward 'good' management of soils, such support could take the form of policy development. A new food-labelling scheme, such as a modified Red Tractor logo, is also recommended for certified sustainably managed soils in order to create societal consumer demand for sustainable produce.

Bioinoculants are agricultural amendments that take advantage of beneficial microbes originating from the rhizo- or phyllosphere, or act as endophytes, in order to stimulate plant health and boost crop yields. A wide range of bioinoculant products of varying efficacy makes it difficult for farmers to select and apply such products with confidence. While bioinoculants are a rapidly developing industry with enormous potential for soil health and sustainable agricultural systems, the current lack of independent quality control over product efficacy claims prevents confident implementation across the agricultural and horticultural sectors. Therefore it is advised to consider the creation of an independent quality control centre where product efficacy is tested, which could be financed by a new industrial levy payment scheme.

The already suggested improvements in communication and knowledge exchange will also help with the management of expectations relating to real-world field applications of modern soil and soil microbiology methods. Innovations in DNA sequencing are resulting in a rapid advancement of scientific knowledge that is difficult for stakeholders to keep up with regarding the functioning of soil ecosystems and soil health. Scientists should communicate better with farmers and landowners regarding how to efficiently convert academic outputs into inexpensive, realistic and quick-to-interpret on-site technology that is farmer-friendly and easy to access.

Communications should also be clear with respect to the time and resources needed to upscale innovations that work at the small scale, implement field trials over a range of soil types and land uses, and monitor innovations in the longer term. In turn, this will also lead to a more realistic understanding of the technology readiness level of the innovation aimed to advance soil health. In order to enhance knowledge exchange, researchers could interact more with organisations such as the Agriculture and Horticulture Development Board that already have effective relationships with the agricultural sector.

Recommendation 6:
The soil health academic community should increase engagement and collaboration with agriculture and industry in order to improve knowledge exchange for effective translation of research outputs into farm-ready affordable innovations, while also developing policy and quality control mechanisms to incentivise sustainable soil management.

A role for soil in food safety for crops. EU COST Action, HuPlantControl – Dr Nicola Holden (Scotland's Rural College, SRUC)

The COST (European Cooperation in Science and Technology) Actions aim to build networks of expertise across EU member states to address strategically relevant and contemporary questions.

The HuPlantControl addresses the issue of contamination of fresh produce by human pathogens. This is a serious problem in horticultural production, with a large proportion of foodborne illness now arising from contaminated produce instead of meat and dairy products. The project has focused attention on bacteria and fungi that cause human disease, because these groups show traits of true biological kingdom-crossers. This issue is embedded in soil health, since it considers the holobiont system of the crop plant, which is ultimately dependent on the soil microbiome.

The project has built on a pan-European network of excellence with a focus on the impact of plant microbiomes on human health. Importantly, it has received excellent support from industry and regulatory authorities, achieving the overall aim of ensuring relevant work, with the applicable outcomes. It has resulted in tangible outcomes aimed at primary producers, those associated with the food industry and public health agencies. The activities range from targeted exchange visits to build research capability, training schools, workshops with primary producers, scientific conferences and stakeholder meetings.

For more information about HuPlantControl visit: **https://huplantcontrol.igzev.de/**.

5.4 Transferring knowledge

Soils are not currently considered a 'common good' protected by a particular Directive, whereas water and air have regulatory frameworks that include actionable indicators. Most of the funding for monitoring our natural environment is therefore allocated to air and water as a direct result of legislation, with less than half a per cent of the funding allocated to soil monitoring. The development and validation of a set of physical, chemical and (micro)biological metrics and indices that are applicable and realistic for many soil types and land uses are needed to implement sustainable soil management for improving soil health and soil ecosystem services. Accordingly, providing appropriate soil metrics and indices would also facilitate the development of soil policy and regulation in support of continuous soil monitoring, thus establishing a robust monitoring framework for all our natural ecosystems.

Soil health innovations could also be advanced via additional mechanisms. These could be established as living laboratories, where researchers collaborate with farmers in the field to develop new innovations; as lighthouses, where farmers evaluate technologies for feeding back to researchers; and through re-establishment of independent field consultants to facilitate knowledge exchange in the agricultural sector. Universities and agricultural colleges could have a role in training this next generation of advisors.

More efficient communication between researchers, farmers and landowners would enhance knowledge exchange towards improving soil health, as already suggested. Further communication initiatives in education, outreach and information sharing in order to raise public awareness of environmental management and soil health are equally relevant. For example, the Microbiology Society might reach out to other learned societies and communities to bridge the communication gap and find the right people to help promote discussions and events, especially outside university cities/towns, to reach a wider audience.

Learned societies and their membership should continue to facilitate the involvement of soil microbiologists in political and political information exchange activities to raise political awareness of (the role of microbes in) sustainable management and soil health with the aim of achieving the UN SDGs.

Recommendation 7:
Funders and the soil health community should support increased education and (re)training of soil health researchers, advisors and sector employees to address a lack in capacity, and should ensure that sector-wide knowledge, skills and competencies are available for successful participation in interdisciplinary projects. The Microbiology Society should align with other societies to help facilitate progress in this area.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PROCEDURE NOTES

6. Acknowledgments

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Appendix

The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet, now and into the future. At its heart are the 17 Sustainable Development Goals (SDGs), which are an urgent call for action by all countries – developed and developing – in a global partnership. They recognise that ending poverty and other deprivations must go hand in hand with strategies that improve health and education, reduce inequality and spur economic growth – all while tackling climate change and working to preserve our oceans and forests. For more information please visit: **https://sdgs.un.org**.

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Page 23: Participants at Annual Conference 2019 – Ian Atherton

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The Microbiology Society is a membership charity for scientists interested in microbes, their effects and their practical uses. It is one of the largest microbiology societies in Europe with a worldwide membership based in universities, industry, hospitals, research institutes and schools.

Our members have a unique depth and breadth of knowledge about the discipline. The Society's role is to help unlock and harness the potential of that knowledge.