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POSTNOTE

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Sustaining the Soil Microbiome

The soil microbiome, communities of microorganisms in soils, underpin natural processes in soil habitats and are affected by environmental and land use change. This POSTnote gives an overview of the benefits provided by the soil microbiome, ways of assessing the soil microbiome, and measures to improve its condition.

Overview

- The soil microbiome refers to the diverse communities of bacteria, fungi and other microorganisms in soil habitats.
- Soil microbes underpin key benefits that soils provide, such as food production, the clean-up of pollutants, and carbon storage in soil organic matter.
- Conventional agricultural practices and climate change can drive changes in soil microbiomes that result in soils providing fewer benefits.
- New genomic and chemical analyses can characterise the soil microbiome, increasing understanding of the roles it performs.
- Protecting and restoring the soil microbiome has both economic and environmental benefits, but there is a lack of studies on measures for achieving this.

Background

Soils are one of the most biodiverse habitats on Earth, with an estimated 4,000 to 50,000 species of microorganism per gram of soil.[1–3] The 'soil microbiome' refers to communities of microbes within the soil, which include bacteria and fungi, but also archaea (single-celled organisms initially identified in extreme habitats), protists (single-celled organisms that, unlike bacteria, contain a nucleus) and viruses.[4] However, although they constitute a large part of the UK's biodiversity, many soil organisms remain unknown. The soil microbiome underpins many of the ecosystem services that benefit humans,[5,6] which include:

- movement and exchange of key plant growth limiting nutrients such as nitrogen and phosphorus;[7]
- protection of plants from stress, pests and pathogens;[8,9]
- decontamination of soils through bioremediation;[10]
- helping to maintain the physical structure of soil;[11]
- decomposition of organic wastes while storing carbon;
- regulating the flow of greenhouse gases, such as carbon dioxide and methane; and,[12]
- a repository of undiscovered biochemicals, including antibiotics,[13] that can be used to address antibiotic resistance (PN 446 and PN 595).[14,15]

Intensive agricultural practices and climate change have affected the state of soils (soil health, PN 502),[12,16] with impacts such as soil erosion. Soil health has been defined in academic literature as the capacity of a soil to function as a living ecosystem to sustain plants, animals and humans, and maintain environmental quality.[17] The range of services that a soil provides will depend on its type or texture (e.g. peat or clay), as well as soil management practices and land use history, all of which have direct long-term effects on soil health and on its associated microbial community.[16,18–20] Soil health has wide-reaching implications for several of the biggest global challenges including food security (PN 556) and climate change (PN 594). The UK Government's 25 Year Environment Plan highlighted the importance of soil health and stated an ambition to manage England's soils sustainably by 2030.[21] It has been suggested that the current requirements of the Common Agricultural Policy do not adequately account for soil health, the soil microbiome or the functions they provide.[22]

Recent technological advances have enabled more detailed study of soil microbiomes, including of the structure and function of microbial communities and to provide insights on how they may be managed. This POSTnote gives an overview of: benefits provided by the soil microbiome, methods for assessing the soil microbiome, pressures changing the soil microbiome, and practices to restore the soil microbiome and support long-term soil stewardship.

Benefits of the soil microbiome

Food security and agriculture

Soil microbes promote plant health by providing plants with access to key nutrients that are often limited in soils, such as nitrogen and phosphorus.[7] Plants attract soil microbes by emitting chemicals from their roots that promote the formation of a relationship between plant and microbe.[23] A key example of this is the mutually beneficial relationship between mycorrhizal fungi and plants. These are fungi that colonise a plant's root system and supply the plant with phosphorus, receiving carbon in return.[24] This is a widespread symbiotic relationship, with an estimated 80% of recorded land plant species associating with these fungi,[25] resulting in widespread connections between plants of different species in terrestrial ecosystems.[26]

Microbes that live independently of plants also play important roles for plant health, including breaking down organic matter in the soil into a mineral form that can be taken up by the plant.[27] Without this, higher levels of fertiliser may be required (see plant breeding and microbiome engineering). Microbes help to stabilise soil particles and maintain soil structure: fungi form long filamentous structures called hyphae that can help bind soil particles,[28] and bacteria and fungi release sticky carbon-rich compounds.[28–30] This stabilisation helps provide a suitable medium for crop roots and to regulate water retention and drainage in dry/wet conditions. Soil microbes have also been identified as an important component of disease-suppressive soils.[31] They protect plants through numerous mechanisms that include:[32]

- boosting the natural immune system of the plant;[33,34]
- producing antibiotic compounds and lytic enzymes (enzymes that break down cell membranes);[35] and,
- competing with pathogens for nutrients or space in soil.[36]

Bioremediation

Urbanisation and industrialisation have resulted in around 300,000 hectares of contaminated land in the UK.[37] Soil microbes can naturally remove many of these contaminants and the use of microbes to decontaminate land is commonplace (bioremediation, Box 1).[38] This is often a cheaper and more environmentally friendly alternative to conventional chemical and physical clean-up methods.[10] Microbes have been successfully used to remediate land contaminated with heavy metals,[39] oil spills,[40] and organic pollutants.[41] However, the success of bioremediation depends on several factors, including soil pH, temperature, nutrient availability and competition with native microbes.[10] Research to promote successful bioremediation is currently focused on two main areas:

- **Bio-stimulation:** supporting native microbes to perform the remediation.[42]
- **Bio-augmentation:** addition of new microbes capable of remediation.[43]

Regulation of Greenhouse Gases

Soil microbes play a fundamental role in the cycling of the three major greenhouse gases; carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O):[12]

- **CO_2.** Soils store approximately three times the total amount of carbon found in vegetation and twice the amount found in the atmosphere.[12,46,47] Disturbance by agricultural practices can stimulate microbial decomposition and respiration, increasing emissions,[48] at an estimated cost of £3.21 bn to the UK annually.[49]
- **CH_4.** Methane is produced through methanogenesis, a process performed by archaea. Bacteria can also reduce emissions by consuming methane in soils.[50] Water levels and soil temperature affect these processes.[51]
- **N_2O.** Intensively fertilised soils act as a major source of nitrous oxide atmospheric emissions,[52,53] as N_2O is emitted predominantly by microbial processes in response to nitrogen fertiliser use.[12] Microbes can reduce emissions by transforming N_2O into nitrogen gas (N_2) if soil conditions are appropriately managed.[52]

Box 1: Case Study – London Olympic Park

Organisations such as the Campaign for Rural England suggest that greater development of disused urban brownfield sites will reduce demand to develop greenfield sites.[44] Around 300,000 hectares of UK soil are thought to be contaminated,[22] and such brownfield sites may need to be remediated before redevelopment. An example of this was for the 2012 London Olympic Games site, located in Stratford, East London, which was a former industrial site, with a legacy of soil and ground-water contamination. Part of the remediation efforts involved using microbes to remove ammonium from the polluted ground-water. Here, bio-augmentation was used: archaea (microbes able to live in extreme environments) were inserted into the boreholes where they degraded the ammonium into nitrogen gas.[45]

Assessing the soil microbiome

Technologies to study the soil microbiome

Over the past decade, the ability to investigate soil microbes has advanced rapidly (Box 2).[54,55] These methods have allowed studies to determine the types, proportions and functions of soil microbes. The next challenge for genomic approaches is to definitively link species to ecological roles (the functions they support, such as nutrient cycling).[7] This has been difficult because attempts to grow soil microbes under lab conditions are often unsuccessful.[56] However, new culturing techniques have been developed,[57] together with alternative methods,[58,59] such as screening cells for gene expression. However, the complexity of the DNA sequence data generated requires analysis by bioinformaticians, a scarce skillset within the environmental science sector.[60,61]

The soil microbiome as an indicator for soil health

Because of the complex nature of soil, defining what constitutes a 'healthy' soil is difficult. It depends on numerous factors, such as location, soil type and purpose. Soils are also dynamic, altering through time in response to environmental and human changes.

Indicators for soil health

Given the role of microbial communities in the functioning of soil, it has been suggested that microbes could be used as a biological indicator to determine soil 'health'.[62] There is no consensus within the scientific community on how best to achieve this, as both microbial communities, and the soils they inhabit, are extremely complex. It has been suggested that comprehensive physical, chemical and biological

Box 2: Analysing microbial communities from soils

Currently, the most common way to analyse the microbial communities from environmental samples is to use fast, automated sequencing methods targeting microbial DNA, summarised below:

- **Step 1: Collect soil samples from the environment.** Sampling needs to take into account that bacterial community composition can vary spatially across different soil depths,[63] and temporally across seasons.
- **Step 2: Extract DNA from the soil sample.** Extraction processes isolate the microbial cells and force them to undergo lysis (break-down). Certain microbes will be more resistant to this process, which may bias the result.
- **Step 3: DNA metabarcoding.** To be able to identify which microbes are present, DNA identifier regions need to be selected and amplified. The slight variation within these sequences allows the bacterial species present to be identified.
- **Step 4: Sequence the samples.** Samples are run through a sequencing machine which determines the gene sequences.
- **Step 5: Bioinformatics analysis.** These sequences are compared to databases to identify what species are present, therefore allowing the determination of microbial community composition within the sample.

indicator approaches would provide an effective assessment (Box 3). However, in the future, it may be possible to combine sequencing data with other datasets, such as previous land use, to develop predictive biomarkers.[64,65]

Standardisation and UK-wide monitoring

The Earth Microbiome Project is a collaborative effort to characterise global microbial diversity, with standardised methods for sample collection, curation and analysis.[66] The Natural Capital Committee have recommended a national survey as part of their proposed environmental census.[67] Developing such a scheme would improve understanding of the state of microbial life within UK soils.[68] The Centre for Ecology & Hydrology are in the process of launching a nationwide soil health monitoring scheme.[69] Consolidating this with data from the Countryside Survey (Natural England's monitoring programme), Scotland's soil repository and agricultural institutes may provide the basis of it.[70–72]

Pressures on the soil microbiome

Arable and dairy farming

Conventional agricultural methods – including intensive tillage (ploughing and harrowing), continuous cropping (growing a single crop species on a field year after year) and extensive use of chemical pesticides and fertilisers – have led to declines in soil quality (PN 502). They adversely affect several groups of soil organisms including fungi and bacteria,[73,74] interfering with ecological processes. These practices are associated with a loss in soil biodiversity,[16] reducing the pool of microbes that plants can form beneficial associations with. The addition of high levels of fertiliser and pesticide alters the communication between plants and soil microbes, decreasing the associations that occur between them.[75] Such practices typically lead to the loss of organic matter from the soil,[76] which is the main food for microbes and essential for a functioning soil microbiome.[77] Studies have also shown that intensive agricultural practices can alter the composition of microbial communities in soils, reducing the soil's capacity to retain nutrients following perturbations, such as drought (see climate change).[78]

Box 3: Indicators of Soil Health

A range of different criteria have been used as soil health indicators:[79]

Physical

- **aggregate stability**: how well soil particles bind to one another and resist disintegration
- **bulk density:** how porous the soil is, indicating if compacted
- **water holding capacity**: the amount of water that a soil can hold

Chemical

- **pH:** affects the soils physical, chemical and biological processes
- **soil organic matter:** this is dominated by the long-lasting organic compounds produced by soil organisms and correlates with many physical and biological properties
- **key nutrients:** such as nitrogen and phosphorus.

Biological

- **earthworm number:** low numbers of earthworms are indicative of poor soil quality
- **respiration:** measures CO_2 release, lower amounts indicate less microbial activity
- **biomass:** the amount of material from living organisms present
- **nutrient cycling:** measures of fluxes of key elements involved in microbial processes such as carbon, nitrogen and phosphorus may give an indication of soil function
- **soil communities:** the different groups of organisms in the soil could indicate the prevailing soil conditions and are likely to respond rapidly to important changes, including the ratio of fungi to bacteria in the soil microbiome.

Urbanisation

It is estimated that over 80% of the UK population now live in urban areas,[80] with 6.8% of UK land being classified as urban in 2011.[81] One major impact of urbanisation is soil sealing, where the ground is covered by an impermeable material, such as a road or building. This has been highlighted as a major source of soil degradation, as it prevents soils from functioning normally.[82] High levels of pollution and changes to urban climate have also been linked with detrimental effects on soil ecosystems.[83] For example, soil pollution has been shown to alter tree-associated fungal communities, resulting in adverse effects on tree health.[84] The structure and function of microbial communities has been found to be significantly altered within urban areas,[85] and this is likely to have knock-on effects on the ecosystem services that soils provide. These services include:[86]

- **provisioning** services, such as food
- **regulatory** services, such as water and air purification
- **cultural** services, such as providing recreational land

Management of urban green space is important as it is the predominant means of carbon storage in urban areas,[87] and networks of green space have been shown to be beneficial for pollinators (POSTbrief 26).[88] The reduction in microbial biodiversity found in some urban sites has been linked to negative consequences for the human immune system.[85,89] However, urban green space can have high microbial diversity and human lifestyle also plays a role in exposure;[56,90] urban dwellers may have less contact with soils. It has been suggested that public awareness of the variety of the benefits that soils provide is limited.[91]

Climate change

The impacts of climate change include: rising temperatures, changes to precipitation, and increased frequency of climate extremes, such as flooding and drought.[92] These are likely to affect soil microbial communities and the ecosystem processes they support.[12] Global changes, such as higher temperatures, have direct effects on microbial metabolism, increasing respiration rates and CO_2 emissions from soils.[93] However, there is debate in the academic literature on whether these changes are short-lived or sustained.[94] Understanding how resilient a soil ecosystem is will help predict its likely response to climate change (Box 4). Studies suggest bacterial communities are less stable than fungal communities to extreme weather events.[95] Soil microbes also play a key role in flood mitigation by protecting the physical structure of soil.[11]

Restoring the soil microbiome

Enhancing the soil microbiome can support the delivery of key benefits, such as carbon storage (Box 5). Restoration approaches will need to be considered on a site-by-site basis, as soils may vary even across a single site. Best practice will differ depending on a range of factors, such as soil type and land-management practice.[96]

Changing land-management practices

Soils are declining in productivity,[97] leading to interest in sustainable land-management practices that can enhance food production.[98] Typically, management practices that reduce inputs of fertilisers and pesticides may result in lower yields in the short-term,[99] but may help long-term maintenance of soil health and the microbiome.

The range of options to improve soil quality are summarised in PN 502. Listed below are methods considered to directly benefit the soil microbiome:

- **Increase soil organic matter (SOM).** SOM provides nutrients for microbes, improves the structure of the soil and enhances soil carbon storage capacity. It can be increased through the addition of cover crops, such as peas or clover,[100] and compost.[101] A key source of SOM may be ‘digestate’ from anaerobic digesters (PN 387),[102] but this can have a lower ratio of carbon to nitrogen than conventional compost, which may affect SOM.[103]
- **Reduce chemical inputs.** These have negative effects on the community composition of soil microbes.[104]
- **Increase the diversity of crops.** On arable or grassland, this increases the soil microbial biomass.[74,105]
- **Reduce disturbance.** Minimal-till management has been shown to increase microbial diversity,[106] but no-till management is not suitable for certain crops such as potato, and can promote weed growth, increasing the need for chemicals. Minimal-till in combination with weed management strategies and sufficient organic matter inputs may offer the optimal approach (PN 501).

Box 4: Ecological resilience

Ecological resilience is the ability of an ecosystem to withstand disturbance before shifting to an alternative state (PN 543). This is considered a desirable quality as it allows ecosystems to respond to environmental change without undergoing dramatic shifts in community structure and function. Research is underway to determine ecosystem ‘tipping points’ (i.e. the conditions that result in an ecosystem transitioning from one stable state to another).[107] Where an ecological community does transition to an alternative state, it can result in large-scale community reorganisation, which is likely to have substantial effects on ecosystem functioning.[107,108]

Targeted approaches

Microbial inoculation

Microbial inoculation, transferring specific soil microbes into a degraded site, has been used in ecosystem restoration.[109] There is a long history of using microbial inoculants, but their success outside of the lab is varied.[110] Several agro-biotech companies are attempting to harness the microbiome. For example, the US company Indigo Ag sources and isolates soil microbes that are associated with plants and coats seeds with these microbes.[111] In theory, this means when the seed germinates it is in contact with a soil microbiome suited to its needs, allowing for greater crop yields without additional chemical inputs.

Plant breeding and microbiome engineering

Several studies indicate that plants can shape their associated microbial communities,[112] which may make it possible to breed plants to acquire certain beneficial soil microbes.[113] Integrating knowledge of how plants recruit their associated microbes into plant breeding practices could lead to the development of crops that need fewer inputs.[114] For example, crops might be bred to produce high levels of compounds that attract beneficial soil microbes, increasing the chance of forming a symbiotic relationship.[7,8] Combining techniques that enhance microbial diversity in the soil, with targeted approaches to increase specific communities of beneficial microbes, or to manipulate key microbial groups, may offer a way to reduce fertiliser use.[7]

Incentivising good practice

The Agriculture Bill 2017–19 introduces a new Environmental Land Management scheme for the funding of environmental public benefits.[115] The Natural Capital Committee have recommended that this should include payments to farmers for improving soil health.[116] Farmers can also drive innovation to improve practices: funding to support research driven by groups of local farmers, along with academic research and consultant support, may help implement approaches to improve soil health.[117–120] Factors such as short farm business tenancies (<5 years) can incentivise short-term productivity over soil health,[68] unless addressed through agreements, payments or regulation.[116]

Box 5: Peat-lands and carbon storage

Peat-lands cover approximately 10% of UK land but store around half of the UK’s soil carbon,[121] approximating 3 billion tonnes,[122] and provide a range of other benefits including wildlife habitats, water filtration and flood prevention The conversion of peat-land into agricultural land lowers water levels, introduces oxygen into the system and increases microbial activity, releasing large amounts of CO_2. More than 80% of the UK’s peat-lands have been classed as degraded emitting an estimated 18 $MtCO_2$ per year.[123,124] In 2018, the government pledged to invest £10 million into UK peat-land restoration schemes. Restoring peat-lands involves raising water levels to create anaerobic conditions and reduce microbial activity, increasing organic matter accumulation and the storage of carbon. However, it can also increase the release of methane, which should be considered when assessing the carbon benefits of restoration schemes.[125]

Endnotes

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