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Fostering Microbial Activity and Diversity in Agricultural Systems

Adopting Better Management Practices and Strategies: Part 1

By Om Prakash Ghimire, Graduate Research Assistant, Department of Plant and Environmental Sciences, Clemson University; Ariana Lazo, Graduate Research Assistant, Department of Agronomy, Purdue University; Binaya Parajuli, Graduate Research Assistant, Department of Plant and Environmental Sciences, Clemson University; and Jaya Nepal, Postdoctoral Associate, Soil and Crop Sciences, School of Integrative Plant Science, Cornell University

Microbes are tiny organisms that are present in our bodies, food, and environment. They are bacteria, fungi, viruses, protozoans, etc. Microbes show distinct functional features in different hosts and environments. This gives rise to the term "microbiome," which is defined as the group of microorganisms residing in a particular system and showing distinct physical and chemical properties, establishing specific ecological niches that are dynamic in nature and vary in different time and space. The composition of microbiomes vary according to different hosts and environments. For example, microbial diversity in the human microbiome is only 10% to that found in the soil microbiome, and the soil microbiome largely consists of bacteria, fungi, archaea, viruses, small protists, and algae (Blum et al., 2019). A gram of soil contains more than 100 million to a billion microorganisms, and less than 1% of these have been characterized (Daniel, 2005; Raynaud & Nunan, 2014). Based on different environments and hosts, microbiomes can be commensal, symbiotic, or parasitic. In this article, we are going to focus on beneficial microbes.

Microbial diversity can be explained as the various range of microbial species, including Bacteria, Archaea, Fungi, Protista, etc. Under the soil ecosystem, bacteria are the most abundant microbial communities, followed by archaea, fungi, etc. (Siles et al., 2018). Microbiomes provide several benefits such as nutrient mobilization and recycling, water holding, organic matter decomposition, high organic carbon and nitrogen content, aeration and fertilizer mobilization, and increased plant productivity and resilience to climate change in agricultural and ecosystem ecology.

This article is the first in a three-part series on fostering microbial activity and diversity through better management practices and strategies. Part 1 will discuss the soil microbiome and its importance along with factors affecting microbial activity in agricultural systems.

Factors Affecting Microbial Activity in Agricultural Systems

Soil microbial diversity varies among different ecosystems and plays a crucial role in regulating nutrient cycling and mobilization, water holding, and organism matter decomposition. The diversity of soil microbes and their functions govern the decomposition of organic matter and release

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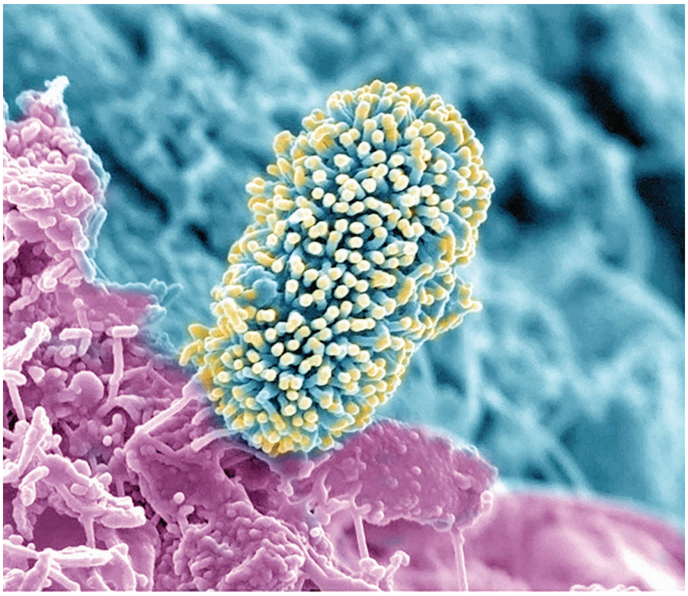

Soil microbial diversity varies among different ecosystems and plays a crucial role in regulating nutrient cycling and mobilization, water holding, and organism matter decomposition. Photo courtesy of Flickr/Pacific Northwest National Laboratory and published under this license: https://creativecommons.org/licenses/by-nc-sa/2.0//

of nutrients, thereby influencing the nutrient availability in the soil. Meanwhile, these activities are highly impacted by soil properties and environmental factors like moisture, soil organic matter, soil texture, pH, precipitation, and aerobic and anaerobic conditions (Girvan et al., 2003; Ghimire et al., 2024).

Soil Characteristics

Various soil textures exhibit different capacities to support microbial communities and their functional characteristics (Sessitch et al., 2001). For example, loam and silt soils typically harbor higher microbial diversity compared with clay and sandy soils. Sandy soils, which are low in organic matter and prone to drought and other environmental stresses, generally host fewer microbes and activity. Moreover, soil pH plays an important role in shaping microbial activity, thereby influencing microbial composition and distributions (Wang et al., 2019). Micro- and macroaggregates within the soil also exhibit distinct microbial diversity and distributions. Upton et al. (2019) reported that microaggregates tend to support higher microbial diversity and possess physical properties conducive to enhanced microbial growth and activity, whereas macroaggregates harbor less diverse microbial communities but offer greater stability in their activity. Similarly, soil bulk density also affects microbial diversity; lower bulk density favors more microbial growth, composition, and diversity while higher bulk density tends to suppress microbial activity.

Soil Organic Matter

Soil organic matter is a source of carbon for microorganisms. For example, humus is a big source of carbon and serves as a slow-release source of carbon and energy. Soil organic matter also contains organic nitrogen, phosphorus, sulfur, and many other elements, and microbes play an important role in recycling these elements through decompositions. The microbes decompose organic compounds to fulfill the microbial nutrient demand. However, the nutrients released from the soil and available to the crop depend on the microbial decomposition and quality of soil organic matter, i.e., the carbon-to-nutrient ratio (Bending et al., 2002). Microbial mass makes up to 1–4% of total organic matter; thus, higher organic matter harbors higher microbial compositions and diversity (Bergtold & Sailus, 2020).

Soil Protein

Soil protein represents a crucial reservoir of the organic nitrogen pool within the soil organic matter, which can be metabolized by microbes and released slowly in the usable form for crops across different growth stages (Hurriso et al., 2018). Soil proteins measure the size of the nitrogen pool in the soil (amino acids and other sources) that can be depolymerized into simpler forms and thus indicate the mineralization rate and availability of nitrogen in the soil. Furthermore, soil proteins serve as substrates for microbial activity, thereby fostering microbial activity and influencing microbial composition and diversity. This interplay between soil proteins and microbial dynamics and diversity serves as a reliable predictor for estimating mineralization rates, thereby contributing to nutrient management in crop production (Geisseler et al., 2019). Thus, soil protein content serves as a critical indicator of soil health and microbial dynamics (Naasko et al., 2024).

Climate

Abiotic factors like moisture availability, precipitation, and temperature exert strong influences on microbial diversity and activity in soil ecosystems. Borowik and Wyszkowska (2016) observed the varied impact of moisture levels on soil microbial communities, abundance, and activities. Climate change, with its multifaceted impacts on agriculture and ecosystems, introduces profound impacts on soil

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microbiomes. Elevated carbon dioxide levels, for instance, have been associated with reduced microbial diversity (Yang et al., 2019), alongside increased mycorrhizal activity and abundance (Dhillion et al., 1995). Changes in precipitation patterns further disrupt soil microbial growth, altering the rate of the soil organic matter decomposition and nutrient cycling. For instance, drought stress exacerbates these effects by modifying soil moisture levels and soil chemistry, impacting soil microbiomes (Naylor & Coleman Derr, 2018). While elevated temperatures initially enhance microbial activity and biomass, prolonged exposure leads to shifts in microbial distribution, diversity, and functional composition (Rasmussen et al., 2020; Zogg et al., 1997). These environmental conditions drive shifts in microbial diversity across diverse agro-ecological systems.

Crop Species and Diversity

Crop species play a pivotal role shaping microbial communities, fostering microbial–plant associations and influencing key functions within agroecosystems. Crop species like grasses, pulses, and other species hold different levels of potential to harbor different microbial communities. Mixed cropping with cereals and legumes increases microbial diversity and composition, facilitating plant-microbe associations (Stefan et al., 2021). Understanding the role of crop species in shaping the microbiome will help in managing farm-level decisions and adopting better practices in different soil and environments in agricultural systems. For example, certain forage grasses have been found to enhance bacterial and fungal diversity, simultaneously increasing nitrifying bacteria like archaea and decreasing denitrifying bacteria (Momesso et al., 2022). Conversely, the cultivation of pulses has shown to augment fungal communities, particularly ascomycetes and basidiomycetes (Yang et al., 2021), whereas cereals like rye can stimulate bacterial communities such as diazotrophs and denitrifying bacteria (Lewin et al., 2024). Thus, diversification of crop species is a promising strategy for fostering microbial diversity and abundance.

Mixed cropping with cereals and legumes increases microbial diversity and composition, facilitating plant-microbe associations. Here, soybeans emerge in a no-till system after terminated cereal rye. Photo courtesy of USDA.

Cultural Practices

Cultural practices such as crop rotation, mulching, cover cropping, intercropping and conservation tillage serve to diversify the soil microbiome, thereby enhancing microbial activity and mineralization processes (Xie et al., 2022). Town et al. (2023) reported that crop rotation schemes incorporating canola, wheat, barley, and pea exert a significant influence on rhizosphere microbiome composition. Similarly, Sun et al. (2023) observed that crop rotation involving pulses led to increased soil carbon and nutrient pools, ultimately enhancing crop productivity. Mulching is also one of the important cultural practices for improving soil moisture retention and reducing moisture evaporation, with profound impacts on soil microbiomes. Wang et al. (2020) reported that mulching enhances soil fungal activity and nitrogen availability. Furthermore, mulching influences temperature, regulates soil aeration, and increases moisture availability, thereby impacting soil chemistry, organic matter decomposition, and nutrient recycling (Shan et al., 2022; Tian et al., 2022). Innovative land management strategies, such as topsoil replacement in eroded soils, have been shown to bolster soil microbial activities, enhance soil health, and increase crop yield (Schneider et al., 2023). Identifying the suitable cultural practices based on crop, environmental, and soil conditions will help to bolster microbial activity and their compositions.

External Inputs

External inputs such as pesticides, fertilizers, and various inoculants play significant roles in modern agriculture practices, yet their impacts on soil microbial activity and abundance vary. Numerous studies have shown that

External inputs such as pesticides, fertilizers, and various inoculants play significant roles in modern agriculture practices, yet their impacts on soil microbial activity and abundance vary. Photo courtesy of the USDA Long-Term Agroecosystem Research Network.

pesticide application, whether foliar or soil based, reduces bacterial diversity and their abundance (Onwona-Kwakye et al., 2020; Jeyaseelan et al., 2023). Similarly, the effects of fertilization are multifaceted; while long-term studies spanning 55 years have shown no significant impact on soil microbial biomass and community composition, short-term effects yield either positive or negative effects on microbial biomass and abundance, which are also dependant on fertilizer dosage (Williams et al., 2013; O'donnell et al., 2001). Organic inputs like biochars and manure applications contribute to enrichment of soil organic matter, consequently bolstering the diversity and abundance of microbial communities, thus helping nutrient recycling and improving crop production (Nielsen et al., 2014). Additionally, the introduction of native microorganisms into degraded soils has been found to enhance soil function and microbial compositions (Dadzie et al., 2024) while microbial inoculants have demonstrated a positive effect on plant and soil health as well as microbial diversity and abundance (Alori et al., 2017). Thus, suitable external inputs can be amended in soil to improve the soil microbial activity and abundance.

Overall, adopting good management practices is vital for establishing the strong foundation for a sustainable future of microbial ecology and nurturing its multifaceted interactions with different components of the soil and environment. Focusing on microbial diversity presents both opportunities and responsibilities for improving and adopting various agricultural practices. Given the pressing issues of global warming, greenhouse gas emissions, and heavy reliance on chemical fertilizers and pesticides in modern agriculture, urgent actions are imperative to mitigate their adverse effects on agriculture and public health. Furthermore, the diverse microbial community plays a crucial role in promoting the health of humans, animals, plants, and soil, aligning with objectives of initiatives like the One Health Initiative (Banerjee & Van Der Heijden, 2023). Thus, prioritizing microbial diversity fosters sustainability, resilience, and innovation across diverse fields, addressing critical environmental, agricultural, health, and industrial challenges and laying the foundations for holistic solutions towards a sustainable future.

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Adopting Better Management Practices and Strategies: Part 2

By Om Prakash Ghimire, Graduate Research Assistant, Department of Plant and Environmental Sciences, Clemson University; Ariana Lazo, Graduate Research Assistant, Department of Agronomy, Purdue University; Binaya Parajuli, Graduate Research Assistant, Department of Plant and Environmental Sciences, Clemson University; and Jaya Nepal, Postdoctoral Associate, Soil and Crop Sciences, School of Integrative Plant Science, Cornell University

Microorganisms play a key role in agriculture and soil health by improving nutrient cycling, organic matter decomposition, water-holding capacity, soil aeration, pH balance, soil structure, etc. Thus, to maximize the benefits of microbial activity, we need to improve the farming practices to improve their abundance and diversity. There are several agronomic and cultural practices farmers can adopt to foster the microbial communities and their interaction with plants to maximize their crop productivity and, in the long term, improve their soil health and sustainability. Higher microbial diversity is also correlated to the increased functional diversity and resilience against different environmental stresses. Improved management practices create favorable conditions for microbial proliferation, leading to their higher activity and abundance and strengthened resilience and stability against environmental disturbances.

This article is the second in a three-part series on fostering microbial activity and diversity through better management practices and strategies. Part 2 will discuss management practices for better microbial activity and diversity.

Management Practices for Better Microbial Activity and Diversity

Crop Diversification

Crop diversification encompasses the cultivation of various crop species in a particular farm or field. This can occur simultaneously (intercropping) or in rotation (crop rotation).

Intercropping involves growing different crop species in the same field during a particular season and is also referred to as polyculture or mixed cropping systems. Commonly grown species include cereals, pulses, and other crops. This practice improves soil bulk density, soil aeration, nutrient mobilization, and soil aggregation and harbors different microbes, thus improving microbial activity and overall soil health. For instance, intercropping of corn with faba bean or pigeon pea has been shown to improve soil micro- and macro-aggregation, microbial biomass, and enzymatic activities (Garland et al., 2017; Tian et al., 2019).

Crop rotation involves growing different crops on the same field in a sequenced pattern or cycle. For example, rotating soybean and maize reduces pathogenic microbial communities while enhancing beneficial

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Intercropping has been shown to improve soil bulk density, soil aeration, nutrient mobilization, soil aggregation, microbial activity, and overall soil health. This photo shows a Kernza–legume intercrop and is courtesy of V. Picasso (originally published in CSA News here: https://bit.ly/45az2vE).

microbes in the soil (Sun et al., 2023). The interaction of the soil microbiome with different crops improves soil organic carbon and nutrients; also, avoiding the repetition of particular crops breaks the pathogen life cycle, reducing disease pressure. Thus, crop diversification promotes crop productivity through soil health and the soil microbiome.

Cover Crops

Cover crops consist of various crop species grown primarily to enhance soil health. These species include grasses like rye, oat, and barley; legumes like clover, lentil, and vetch; and brassicas like radishes and mustards. Cover crops offer various benefits to soil health, including erosion control, soil fertility improvement, weed suppression, soil moisture maintenance, breaking of compact soil layers, and improving nutrient mobilization (Poeplau & Don, 2015; Blanco-Canqui et al., 2011). For example, legume cover crops like lentils and vetch are capable of fixing atmospheric nitrogen and releasing abundant amino acids and sugars as root exudates, thereby promoting beneficial bacterial and fungal communities (Cazzaniga et al., 2023). Thapa et al. (2021) observed that incorporating cover crops in a mixture with legumes improved soil fungal abundance, enzymatic activities, and overall soil biological health under wheat–sorghum rotations in semi-arid ecosystems. Similarly, Chavarria et al. (2016) reported that utilizing a mixture of cover crops as a crop diversification strategy improves soil microbial diversity and enzyme activities in corn–soybean cropping systems under humid conditions. Thus, cover crop adoption promotes a sustainable future for soil health and the soil microbiome.

Mulching

Mulching is a practice of reducing the exposure of the soil surface area to direct sunlight, which checks moisture evaporation and weed growth and maintains moisture and temperature in the soil, promoting soil microbial activity and abundance. Mulching serves as a positive factor for increasing crop growth, yield, and use of water and nutrients (Lal, 1974; Mulumba & Lal, 2008; Qin et al., 2015). The mulching materials can be dead plants and their parts, artificial mulch like plastic, and living mulches like cover crops. Several studies have reported the enrichment of bacterial and fungal activities and abundance due to mulching with more positive results in organic mulching (Tian et al., 2022; Zhang et al., 2020). Thus, mulching can be a very effective tool in boosting crop yield, soil health, and microbial activity and abundance in soil and promoting climate-resilient agriculture.

Livestock Manure

Raising livestock at farms can be beneficial for meat and milk purposes as well as for manure. Livestock manure has been used as a source of nutrients for centuries in agriculture. Several studies have shown application of dairy manure, poultry manure, and other animal manures increased soil organic matter and organic carbon, nitrogen, and water-holding capacity in the soil and was associated with higher microbial biomass, activity, and abundance (Rayne & Aula, 2020; Wan et al., 2021). One-hundred-year-old experiments on applying manure in the Knorr-Holden Plot in Nebraska have shown increased soil organic matter, nitrogen, and phosphorus in the soil and provided stable yield and sustainable maize production systems (Maharjan et al., 2021). Some manures like poultry manure supply more nitrogen than other manures and also differ in other nutrients. Thus, different manures hold different physical and chemical properties, and applying them at different combinations can be beneficial in enhancing microbial activity and their abundance and ultimately enhancing nutrient mobilization and resulting in better soil and higher crop productivity.

Manure itself has various microbial communities and is rich in nutrients. Jangid et al. (2008) observed the addition of poultry litter improved the bacterial richness and evenness. The addition of liquid swine manure reduced the pathogenic microbial communities and pathogen infestation in potato fields (Conn & Lazarovits,

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Several studies have shown application of manure increased soil organic matter and organic carbon, nitrogen, and water-holding capacity in the soil and was associated with higher microbial biomass, activity, and abundance. Photo by Sarah Brickman.

1999). The addition of manure also increased the organic carbon inputs, improving the soil organic carbon (Haynes & Naidu, 1998).

Organic Amendments

Organic amendments are various organic inputs in the soil to improve soil biological activity and overall soil health through microbial activity and abundance. These include crop residue, manure, composts, biochar, and many others. When crop residues are reintegrated into the soil, they serve as a vital organic carbon and nutrient for crops and soil microbes. As these residues decompose, they augment microbial biomass, activity, and diversity, thereby fostering soil aggregation and soil health. Moreover, the ongoing decomposition of these residues contributes to the formation of soil humic mass and recalcitrant organic matter, further enriching soil quality. For instance, maize and sugarcane crop residues enhance the humic mass content and soil aggregation, thereby promoting soil biological health (Liu et al., 2021; Zhang et al., 2021). Biochar, a charcoal-like substance that is enriched in carbon, is produced by burning organic materials from various agricultural sources. Its intricate structure renders it highly resistant to microbial decomposition, thereby enhancing soil's capacity to sequester organic matter and nutrients. Additionally, biochar application enhances the soil microbiome, leading to improved wheat performance and mitigated pesticide accumulation in wheat by increasing root–microbiome interaction, particularly under stressful conditions (Meng et al., 2019). Similarly, compost production involves the decompositions of the waste and humus materials, yielding a valuable fertilizer and nutrient source for crop production. Application of compost enhances nutrient availability and improves the growth and productivity of crops such as corn, wheat, etc. (Aiad et al., 2021).

Plant Growth-Promoting Microorganisms

Introduction of beneficial microorganisms like nitrogen-fixing bacteria and mycorrhizae through inoculation have been shown to improve crop production and soil health (Li et al., 2022). Microbial inoculation requires using proper methods that consider crop species, soil condition, and the environment for better results (Lopes et al., 2021). Understanding the interaction of plant–microbial association is key to successfully adopting application of microbial inoculum as biofertilizer for enhancing crop production and reducing fertilizer inputs. Abd-Alla et al. (2014) observed that dual inoculation of rhizobia and arbuscular mycorrhizal fungi in faba beans improved crop performance through efficient acquisition of soil nutrients and nitrogen fixation while studies reported yield increase in corn, soybean, and cotton (Megali et al., 2015; Khaitov et al., 2019). Inoculation of microbial communities, especially the native microbiome, enhances soil microbial diversity, restores the soil health, and increase crop productivity (May et al., 2023; Zhou et al., 2023). Thus, inoculation of microbial communities as biofertilizers holds a strong promise for improving soil health and crop yield through fostering microbial communities.

Reduced Tillage

Tillage exerts disturbance in soil, causing the breakage of soil aggregates and exposing both the soil and its microbiome to sunlight. This alters the physical and chemical properties of the soil, leading to the decomposition of carbon protected within aggregates. Consequently, it results in low organic matter, diminished water and nutrient retention capacity, and a shift in the soil microbiome compositions (Rieke et al., 2022). Reduced-tillage

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Reduced-tillage practices, enhance soil organic matter content, which serves as a vital energy and nutrient source for the microbial community. Photo by Nall Moonilall.

practices, on the other hand, enhance soil organic matter content, which serves as a vital energy and nutrient source for the microbial community, fostering the increase in microbial activity, altering microbial composition, and promoting the arbuscular mycorrhizal fungi and bacteria involved in decomposing organic matter (Hungria et al., 2009; Van Groenigen et al., 2010). Parajuli et al. (2021) observed that reduced tillage improves soil organic carbon, microbial biomass, and microbial activity in corn–cotton–soybean rotation systems while boosting the active pool of organic carbon and nutrients in the soil. Thus, reduced tillage emerges as an alternative approach to enhance crop productivity and soil health by fostering increased microbial activity and abundance.

Soil Conservation

Soil conservation practices like no-till or reduced tillage, residue retention, cover cropping, diversified and extended crop rotations, and other soil management practices hold a strong promise in promoting soil health by increasing soil organic matter, soil organic carbon and nitrogen, soil aggregates, high microbial activity, and other physical and chemical properties of soil. Soil microbiomes mediate the soil aggregation through cementation and binding of soil particles by releasing different metabolites and biofilms (Kremer & Veum, 2020). Soil aggregates further help in improving soil fertility and crop productivity, along with increasing soil microbial biomass, microbial enzyme activity, and microbial abundance (Veum et al., 2015; Pellegrino et al., 2022), thus reflecting soil conservation practices as a tool in soil health and soil microbiomes.

Soil conservation practices can promote soil health by increasing soil organic matter, soil organic carbon and nitrogen, soil aggregates, high microbial activity, and other physical and chemical properties of soil. Photo by Jaya Nepal.

Precision Agriculture

Precision agriculture holds strong promise for maintaining soil health and microbial activity in soil. With the help of precision agriculture tools, farmers can monitor the plant growth and soil moisture and nutrient status in real time. This helps in optimizing irrigation and nutrient management, and thus, maximizing the microbial activity and abundance in soil, which will ultimately help in mobilizing nutrients, decomposing soil organic matter, and increasing organic carbon and nitrogen content in soil (Borowik & Wyszkowska, 2016). Similarly, precision tools mediate disease, and pest monitoring helps to reduce the application of pesticides in the field, which will again reduce their

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negative impacts on soil microbiomes (Lo et al., 2010). Thus, precision agriculture opens several avenues in monitoring plant and soil health and different functional properties and traits, thereby, adopting and improving farming practices to improve soil health and soil microbiomes and attain better yields and productivity.

Inorganic Fertilizers

Fertilizers are essential components of agriculture, impacting crop growth, development, and ultimately, yield. The choice of fertilizers and their dosages influences soil microbiomes. The effects of fertilization on soil microbiomes are multifaceted. For instance, a long-term study spanning 55 years has shown no significant impact of inorganic fertilizers on soil microbial biomass and community composition, whereas short-term effects have been reported as either positive or negative on yield (Williams et al., 2013; O'Donnell et al., 2001). Thus, proper dosage of inorganic fertilizers improve soil fertility and nutrient availability, thereby improving microbial activity and abundance.

Sanitation

Sanitation is another important step in adopting better farm practices to increase microbial activity and abundance in the soil. Proper disposal and removal of diseased plants and their organs, along with sanitary measures to check the infestation and spread of diseases and pests from neighboring fields, will reduce the disease pressure and thus frequency of pesticide application in the field (Salamanca, 2015). The reduced application of pesticides will benefit beneficial soil microbes and maintain the health of the soil.

Soil Testing

Soil testing in the field can be crucial in decision-making regarding agricultural practices aimed at maximizing soil health and crop productivity, considering microbial activity, abundance, and compositions (Karlen et al., 2019). Soil tests help understand nutrient content, pH, and electrical conductivity, facilitating the design of fertigation schedules. Measuring bulk density aids in determining the amount of additional manure needed to improve soil aeration. Additionally, DNA sampling from soil helps identify microbial diversity and abundance. Thus, adopting a strategy to increase microbial diversity and abundance will ultimately enhance nutrient recycling and boost crop productivity

Soil testing in the field can be crucial in decision-making regarding agricultural practices aimed at maximizing soil health and crop productivity. Photo by Briana Wyatt.

Soil Replacement and Landscape Rehabilitation

Innovative land management strategies, such as topsoil replacement in eroded soils, have been shown to bolster soil microbial activities, enhance soil health, and increase crop yield (Schneider et al., 2021, 2023). Topsoil replacement will be an important strategy in a landscape prone to soil erosion where soil fertility and soil health have been diminished to the extent of making the area unfit for crop cultivations. Schneider et al. (2023) reported that soil landscape rehabilitation increased organic carbon, nutrient availability, water infiltration rate, fungal and bacterial populations, and overall soil health, which indicates that rejuvenating the soil's microbial activity and abundance will help in rehabilitating the poor soil into cultivable soil.

Soil Fertility and Nutrient Management

The biodiversity of microbial populations is essential in soil fertility and nutrient management. These diverse populations of microbes are critical for the mobilization of nutrients for plant availability, rhizosphere interactions, and many other functions integral to soil and plant health (Sabir et al., 2021). Given the niche role various microbes play in soil and plant health, it's important to recognize

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Effective moisture management, such as through irrigation, is essential for sustaining soil health and microbial communities. Photo by Udayakumar Sekaran.

how different nutrient management strategies can affect microbial populations and activities. A beneficial management practice that can bolster microbial communities and soil health is using organic fertilizers in agricultural systems. Most agronomic systems implement inorganic fertilizers to boost crop growth by providing plant-available nutrients; however, the extensive use of these fertilizers has resulted in acidification of our soils, leading to repercussions on native microbial communities (Ozlu & Kumar, 2018). An alternative to chemical fertilizers has been organic fertilizers, derived from plant or animal-based materials. These organic fertilizers have the potential to enhance biogeochemical cycling, provide slow-release plant-essential nutrients for plant uptake, and increase the diversity of rhizosphere microbial populations (Yu et al., 2024). The significance of the effects on microbial communities and soil health can vary depending on the source of the organic fertilizer; however, organic fertilizer serves as a beneficial alternative that can enrich microbial diversity and activity (Cesarano et al., 2017; Yu et al., 2024).

Irrigation Management

Soil moisture is a critical factor in maintaining microbial diversity, impacting various aspects of microbial life from respiration to metabolic functioning (Borowik & Wyszkowska 2016; Van Horn et al., 2014). Different moisture levels can lead to diverse responses within microbial communities with some species thriving in moist conditions and others preferring slightly drier environments, influenced by acidity and alkalinity levels induced by varying moisture levels. Additionally, moisture content also affects nutrient availability, shaping the composition and distribution of the microbial populations. Soil texture also influences microbial activity under moisture stress as demonstrated by recent research (Siebielec et al., 2020) showing that loamy soil exhibits greater resilience in bacterial activity during drought stress compared with sandy soil. Some studies also reported that increases in rainfall can elevate methane flux and influence microbial biomass and organic carbon contents (Wu et al., 2021). Therefore, effective moisture management, such as through irrigation, is essential for sustaining soil health and microbial communities, ultimately contributing to increased crop productivity.

Disease and Pest Management

Another benefit of a diverse microbiome is its contribution to soil–plant system resilience against soil-borne pathogens and pests. Conventional agriculture has typically used pesticides to reduce the effects of disease and pests on crop health and yields. However, pesticide usage can have ramifications on indigenous soil microbial communities; affecting the microbial diversity and activity in the soil, along with posing the potential risk to environmental and human health (Lo, 2010; Rani et al., 2021). Studies have shown that a diverse, functional microbiome can inhibit the development of diseases by combating soil-borne pathogens and insect pests (Hu et al., 2016; Wang & Li, 2019; Francis et al., 2020). In the study performed by Hu et al. (2016), it was reported that greater *Pseudomonas* density and diversity negatively correlated with pathogen density, leading to decreased disease incidence.

Due to the ability of active and diverse microbiomes to suppress disease and pests both directly and indirectly, microbes have been implemented as biocontrol agents as part of an integrated pest management (IPM) strategy and as an alternative to pesticides (Elnahal et al., 2022). The addition of microbial inocula of native soil microbes has been explored as

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disease and pest control management, manipulating the microbiome to enhance "soil immunity" and protecting crops through plant–microbe relationships (Gadhave et al., 2016). Other management strategies that can assist with disease and pest suppression are those that magnify microbial diversity such as crop rotation (Peralta et al., 2018) and the addition of organic amendments (Akanmu et al., 2021).

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STUDENTS

Fostering Microbial Activity and Diversity in Agricultural Systems

Adopting Better Management Practices and Strategies: Part 3

| **By** Om Prakash Ghimire, Graduate Research Assistant, Department of Plant and Environmental Sciences, Clemson University; Ariana Lazo, Graduate Research Assistant, Department of Agronomy, Purdue University; Binaya Parajuli, Graduate Research Assistant, Department of Plant and Environmental Sciences, Clemson University; and Jaya Nepal, Postdoctoral Associate, Soil and Crop Sciences, School of Integrative Plant Science, Cornell University

This article is the third in a three-part series on fostering microbial activity and diversity through better management practices and strategies. Part 3 will discuss monitoring and quantification of microbial diversity, challenges for adopting sustainable practices, government policy, and scaling microbial diversity from smaller to larger agricultural systems.

Monitoring and Quantification of Microbial Diversity and Its Impacts

Soil microbial diversity is a black box and requires more intensive study to understand the effects of various strategies on ecosystem functions. The monitoring and assessment of soil microbial activity, abundance, and diversity will help us predict the associated soil properties and processes for assessing the soil health and impacts on crop production. Various methods are employed to monitor and quantify the soil microbial communities. Most of these methods need sophisticated tools and controlled environments, which may not be available for farmers but are definitely available at local university, government, and privately run labs.

Plate and direct counts involve culturing microorganisms on media and counting them under a microscope, primarily detecting culturable microbes (Bakken, 1997). Phospholipid fatty acid analysis (PLFA) extracts and analyzes phospholipids from microbial cells, differentiating bacterial and fungal groups. Real-time polymerase chain reaction (PCR) measures DNA amplification to quantify the microbial community quantitatively but lacks qualitative insights. Gene sequencing assesses alpha and beta diversity, offering a qualitative understanding of microbial communities resulting from different management practices. Enzymatic activity assays are commonly used to understand soil microbial roles in carbon and nutrient cycles by breaking down compounds into simpler forms. Soil enzymes, mainly extracellular, play a crucial role in decomposing organic compounds with hydrolytic and oxidative enzymes involved in carbon, nitrogen, and phosphorus cycling. Another method, the BIOLOG EcoPlate, assesses community-level physiological profiling (CLPP) by providing 31 carbon substrates and measuring microbial metabolic potential through color development and optical density at 590 nm (Garland & Mills, 1991). These techniques offer valuable insights into soil microbial functions and their contributions to ecosystem processes.

Researchers are increasingly concerned about the disparity between soil microbial exploration in laboratory settings and real-world field conditions. There is a

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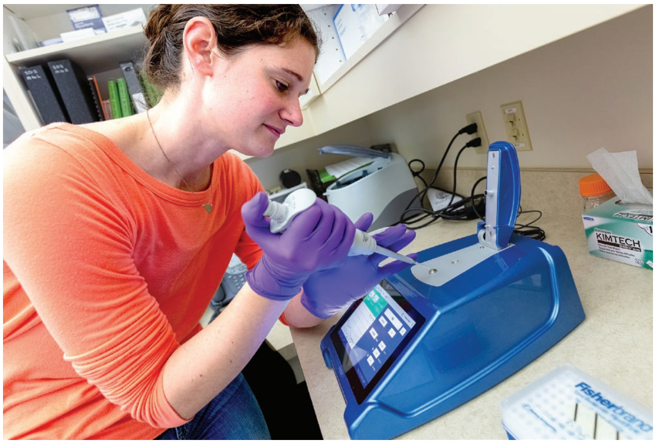

Spectrophotometer for real-time polymerase chain reaction (PCR) testing, which measures DNA amplification to quantify the microbial community quantitatively. Photo by NPS/Jacob W. Frank and published under this license: https://creativecommons.org/publicdomain/mark/1.0/.

pressing need for a farmer-friendly and comprehensive approach for rapid on-farm assessment of soil microbial diversity, which could facilitate a more accurate correlation between soil microbial diversity and soil functions as well as ecosystem services.

Challenges of Adopting Sustainable Practices to Foster Soil Microbial Health

There are several challenges and limitations in advancing microbial diversity.

Financial Burden

Money and resources are always significant criteria for farmers and other agricultural managers throughout the growing season. To test for microbial populations, farmers typically send soil samples to commercial or extension laboratories for analysis; however, testing can be costly depending on the materials/technology necessary for analysis and the number of samples. Microbial inoculants for in situ enhancement of microbial populations may also be expensive depending on the acreage and the frequency of application needed for desired influence in the soil microbiome. Adopting cultural practices like conservation tillage, crop rotation, intercropping, and cover crops will build up microbial activity and diversity in the long run; however, they could pose a financial burden to the farmers in the short term. A recent study (Pathak et al., 2024) has shown that farmers are likely to discontinue cover cropping and conservation tillage when there is no government funding available, which shows that there is a need to support farmers financially to achieve the goal of a sustainable future through microbial farming.

To test for microbial populations, farmers typically send soil samples to commercial or extension laboratories for analysis; however, testing can be costly depending on the materials/technology necessary for analysis and the number of samples. Photo by Peggy Greb.

Agronomic Challenges

Agronomic management practices play an immense role in enhancing microbial diversity and activity. Shifting agricultural management from a conventional system to management practices such as cover cropping, crop rotation, and/or conservation tillage can beneficially magnify the microbial population. Shifting between management practices can be difficult, especially considering the benefits may appear gradually over the long term. Farmers may find it difficult to continue practicing management alternatives when they have a slew of immediate problems such as increased weed pressures with conservation tillage (Kumar et al., 2020).

Another challenge in agronomic systems is the effect of pesticides on native microbial populations. Depending on the type of pesticide applied and the growing crop, the application of pesticides may alter microbial populations and/or affect their niche roles within the soil–plant

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While organic fertilizers are a fantastic alternative to inorganic fertilizers for stimulating microbial activity in the soil microbiome, contaminants could be a concern depending on the fertilizer source. Photo by Rebecca Ryals and originally published here: agronomy.org/news/science-news/getting-solid-soil-response-biosolids-application.

ecosystem (Yu et al., 2023) With the additional influence of increased weed pressures from sustainable management practices, increasing the frequency of pesticide application leads to indirect and direct effects on the microbial population (Lo, 2010; Yu et al., 2023).

Human Health Risk of Organic Fertilizers

As discussed earlier, organic fertilizers are a fantastic alternative to inorganic fertilizers for stimulating microbial activity in the soil microbiome; however, depending on the source of the organic fertilizer (animal waste, compost, or biosolids), contaminants of concern such as heavy metals, pharmaceuticals, and hormones may be entering the soil and be available for plant uptake or may enter water resources (Goss et al., 2013; Urra et al., 2019). Not all organic fertilizers have these contaminants of concern as it entirely depends on the source and the treatment of these organic fertilizers in preparation for agricultural application; it is important to recognize the potential of introducing these contaminants of concern to our food and water resources.

Education

Finally, the last and probably most important challenge is educating agricultural managers, farmers, and home gardeners on the essentiality of a diverse and active soil microbiome in crop production. Microbes tend to have a bad reputation with the general public, mainly known to be harmful to human health and causing disease. While this is not inherently incorrect, it is still a misperception as there are a multitude of beneficial microbes that are necessary for everyday life. It is important to improve microbial literacy so that agricultural managers and home gardeners can make informed decisions for their agroecosystems (Bloom et al., 2024).

Government Policy: Regulations and Interventions

In recent decades, there's been a notable surge in microbiome research, particularly in agricultural contexts aimed at bolstering crop production amidst climate change. While soil management is vital for climate-resilient agriculture, focusing on soil microbiome diversity is crucial for sustainability. Understanding these interactions is key to optimizing microbe benefits. Thus, a strong government policy is needed to effectively incorporate the policy of diversifying and harnessing the microbiome's potential. The soil microbiome has been further integrated to the One Health initiative where microbes are recognized as integral components of human animal and ecological health. This underscores the importance of soil microbiome research and development as a cornerstone of achieving One Health (Banerjee & Van Der Heijden, 2023).

There have been many initiatives from the U.S. government in promoting the study of microbiomes in a broader perspective and exploring their potential. In 2016, the U.S. government launched the National Microbiome

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The U.S. government's 2023 farm bill incentivizes the use of biologicals, which can improve root traits, nutrient cycling, and carbon sequestration, ultimately reducing greenhouse gas emissions and increasing return on investment. Photo by Carolyn Opperman and originally published here https://acsess.onlinelibrary.wiley.com/doi/10.1002/crso.20263.

Initiative (NMI), investing more than $121 million to advance cross-ecosystem microbiome studies, which profoundly impact human health, food security, and ecosystem functioning (White House Office of Science and Technology Policy, 2016). Similarly, the Food and Drug Administration (FDA) has implemented regulations for monitoring the impacts of FDA-regulated products on microbiomes. The U.S. government's 2023 farm bill prioritizes soil carbon capture and storage, emphasizing strategies to enhance microbial activity and diversity in agricultural systems, underlining the importance of policymaking in implementing microbiome-based strategies while preserving agricultural soils (Tao et al., 2023). The bill incentivizes the use of biologicals, which can improve root traits, nutrient cycling, and carbon sequestration, ultimately reducing greenhouse gas emissions and increasing return on investment. Through the Inflation Reduction Act (IRA), the U.S. government allocated $20 billion for conservation and climate-smart agriculture and $300 million for actions addressing soil carbon improvement, nitrogen loss reduction, and mitigation of agriculture-related greenhouse gasses and microbial biodiversity. Furthermore, the National Institute of Food and Agriculture (NIFA) under USDA has prioritized research funding towards agricultural microbiomes, aiming to enhance productivity, sustainability, food safety, and carbon sequestration in agricultural systems while addressing knowledge gaps in agricultural microbes and microbiome functions across different scales of agricultural ecosystems through innovative projects (NIFA, 2023). Going further, the government should develop a pricing formula to reward farmers or farms that sequester more carbon, thereby encouraging them. Additionally, to achieve the goal of net zero emissions by 2050 in the U.S., we must reduce emissions from agriculture where microbiomes will play a crucial role (Kerry & McCarthy, 2021).

Scaling Microbial Diversity From Smaller to Larger Agricultural Systems

Microbial communities and their diversity are crucial for ecosystem resilience (Shade et al., 2012). Adopting agroecological principles like maximizing biodiversity and promoting soil cover enhances soil organic matter and microbial activity and diversity, leading to improved carbon sequestration, water infiltration, wildlife habitats, and profitability (Prommer et al., 2020). Microbes play a vital role in soil health and crop growth while providing ecosystem services to combat climate change (McBratney et al., 2014). Scaling up practices to promote beneficial soil microbes globally requires continuous improvement

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Adopting agroecological principles like maximizing biodiversity and promoting soil cover enhances soil organic matter and microbial activity and diversity, leading to improved carbon sequestration, water infiltration, wildlife habitats, and profitability. Photo by Gurbir Singh.

in farming practices and support for farmers to adopt sustainable methods, ensuring soil health, carbon sequestration, and food security.

Conventional farming persists due to the pressure of global food demand, yet strategies can mitigate its environmental impact. Implementing crop rotation, intercropping, and reduced synthetic inputs in conventional farming enhances microbial diversity and reduces soil disturbance (Labouyrie et al., 2023). Organic farming fosters richer microbial diversity than conventional methods, benefiting from practices like crop rotation, organic inputs, and increased plant diversity (Hartmann et al., 2015; Lori et al., 2017). Scaling up organic farming and adopting its standardized practices can lead to a sustainable future.

> **"...there can be no life without soil and no soil without life; they have evolved together."**
>
> **—Charles Edwin Kellogg**

Urban gardening, though small in scale, contributes significantly to food security and sustainability through practices like composting, mixed cropping, and animal farming (Bonanomi et al., 2016; Lupatini et al., 2017). Permaculture and conservation agriculture emphasize holistic approaches, promoting soil health and microbial diversity through reduced inputs and whole-system management (Symanczik et al., 2017; De Tombeur et al., 2018; Jia et al., 2022). These practices offer promising pathways toward sustainable agriculture and climate resilience.

Conclusion and Future Directions

At this pivotal moment, optimism surrounds the evolving understanding of the role of microbes in agroecosystems, yet caution is warranted amidst increasingly complex global challenges. Embracing the task of scaling up microbial knowledge to a global level can lead to a more sustainable and resilient agricultural future. A thriving soil microbiome forms the bedrock of sustainable agriculture, driving ecological functions and contributing to nutrient cycling, soil structure maintenance, plant growth, and carbon capture. Nurturing microbial activity and diversity is

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vital for preserving soil fertility, mitigating climate change impacts, and ensuring long-term food security. While promising practices like reduced tillage and regenerative agriculture show potential, the future lies in harnessing plant–microbe partnerships and leveraging technologies like gene editing to engineer beneficial microbial strains. Robust policy support and advocacy efforts are needed for widespread adoption of ecological practices to enhance the soil microbiome. Farmers, policymakers, researchers, and the public must collaborate to develop comprehensive soil health strategies, implement evidence-based practices, and quantify the benefits of agroecological approaches. Through collective efforts and a commitment to soil stewardship, we can unlock the soil microbiome's full potential, restoring degraded soils, enhancing food security, and mitigating climate change for a sustainable future.

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