Natural Capital: Economic Incentives and Science-Based Targets for Integrated Soil Microbiome Solutions in Agriculture

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1. Executive Summary

The modern agricultural economy is fundamentally dependent on several conditions including the sustained services provided by the soil microbiome. However, the microbiome's ecological worth has not been widely understood, valued, or protected in modern industrial practices. As such, human intervention and extractive agricultural practices have degraded over a third of the world's fertile soils and continue to threaten the remaining stock.[1]

To mitigate this growing threat to global food security and provide an environmentally sustainable path forward, it is crucial that:

1. **Agricultural institutions understand the inherent economic and ecological value of the soil microbiome as an asset class.**

2. **Nature-Based Solutions that enhance the functions of the soil microbiome are established and well-publicised, allowing farmers to avoid management practices that harm the microbiome and embrace beneficial solutions that generate restorative practices.**

3. **Frameworks for microbial monitoring are increasingly available which enable the implementation of Science-Based Targets specifically oriented for the soil microbiome.**

4. **Businesses recognize the potential for integrated microbiome solutions that utilize network science to create dynamic soil health signatures and facilitate precision microbiome management.**

5. **Financial players understand the value of science-based microbial signatures that are predictive of ecosystem services and create value-based approaches and financial incentives to drive regenerative agriculture and biodiversity conservation, carbon sequestration and resilience.**

The advances in understanding the networks of microbes and their relationships with ecosystem are gaining pace. Work linking patterns in these networks to predictive signatures opens the way for a new approach to valuation and conservation of land and regenerative practices in agricultural settings. However, this is a complex field and conventional science struggles to make meaningful connections that can be correlated and have potential to be scaled.

The usage of data science in agriculture is rapidly growing across the industry[2], presenting a valuable opportunity for the integration of microbial data into these more conventional systems. It is essential that businesses recognize the financial materiality of the soil microbiome and the potential for integrated microbiome solutions that harness the microbiome's intrinsic agricultural benefits. In time, it is anticipated that an understanding of the live and dynamic nature of the soil will give way to asset classes that include soils to conserve biodiversity, soils to retain water, soils that are agriculturally productive and soils that can be termed 'Carbon Sinks' to complement the existing classes of land such as farmland and real estate.

Adopting solutions that focus on the soil microbiome's health aligns with the rising global demand for sustainable and regenerative agricultural practices. Moreover, it challenges current strategies for carbon sequestration to align themselves with quantifiable science-based indicators, reaffirming that carbon is being effectively stored. This report highlights the financial incentives and environmental benefits of some of these solutions, while providing a foundational overview of the necessary components for integrated microbiome solutions. However, further research and field studies will be necessary to fully materialize these solutions and further testing to predict the outcomes at a level of scale.

2. Introduction

The Soil Microbiome

Microbiomes are intricate communities of microorganisms that inhabit terrestrial and aquatic ecosystems, as well as those associated with hosts, including plants, animals, and humans. Their functional diversity and adaptability play a significant role in influencing a variety of environments.

The soil microbiome encompasses diverse and complex communities of microorganisms, including bacteria, fungi, archaea, protozoa, and viruses inhabiting the soil environment[3]. These microbes play fundamental roles in supporting soil health through cycling nutrients, decomposing organic matter, and promoting plant growth. The interactions within the soil microbiome are incredibly complex, often featuring millions of distinct species contributing to different ecological processes. Whilst it is a critical component of terrestrial ecosystems and holds the potential to fundamentally alter the health of both agricultural and natural environments, many of its intricacies lie undiscovered.

The Problem at Hand

Human activities have significantly altered the soil microbiome, causing large-scale consequences on soil fertility[4]. Intensive agricultural practices, such as the overuse of agrochemicals and monoculture cropping have had detrimental effects on diversity and abundance, and likely function[5]. Deforestation, urbanization, and other forms of land use change have likewise damaged native microbial communities and the assembly of their architectures, hindering their ability to perform essential ecosystem services. Understanding the importance of the soil microbiome, in addition to the far-reaching effects of human-induced changes is crucial for developing long-term land management practices that support sustainable soil health and restorative agricultural practices.

The rising threat of soil fertility loss from degradation and erosion poses a significant risk to agricultural sustainability and long-term food security. As land use continues to disrupt the soil microbiome, fertile topsoil is increasingly threatened through nutrient depletion, soil erosion, contamination, and compaction. According to the Food and Agriculture Organization (FAO), roughly 33% of global soil is “moderately to highly degraded”, a figure which could rise to 90% by 2050[6]. Moreover, the Global Soil Partnership (GSP) estimates that the world loses about 75 billion tons of fertile topsoil annually[7]. Addressing the drastic decline of soil fertility demands urgent action across the agriculture industry through the adoption of sustainable farming practices and innovative microbiome-based solutions.

3. The Natural Capital of the Microbiome

The term ‘natural capital’ refers to the Earth's stock of both renewable and non-renewable resources that provide services to humanity. The natural capital perspective on economics recognizes the value of the Earth's ecosystems, biodiversity, and natural resources in sustaining life, supporting economies, and enhancing human well-being[8].

The soil microbiome is a vital component of the natural capital model, as microbes contribute to many elements including soil health, plant nutrition, ecosystem services, biodiversity conservation, water quality, climate regulation, human and animal health and wellbeing, and ecosystem resilience. Understanding and enhancing the natural roles of microbes in natural and agricultural ecosystems is essential for sustainable resource management and human health. Being able to exploit these microbes in useful and responsible ways is the currency of the forthcoming bio-revolution.

The Role of the Microbiome in Ecological Processes

The microbiome is an essential part of balance in agricultural ecosystems, contributing to many of the fundamental processes that support and provide life often known as ecosystem services. Understanding the significance and value of the soil microbiome within the environment can enable businesses to achieve widespread ecological and financial benefits within the agriculture sector. There are many key activities modulated by microbes within the microbiome.

1. **Nutrient Cycling**
   Microbes are prominent drivers of nutrient cycling and mobilization within ecosystems. They play important roles in the biodegradation of organic matter and release of nutrients, and the solubilization of insoluble minerals for uptake by plants. They are key components of major biogeochemical cycles, including Nitrogen, Carbon, and Sulfur. Microbes mediate processes like nitrogen fixation, denitrification, and methanogenesis,

influencing greenhouse gas emissions, soil carbon sequestration, and nutrient availability[9].

2. **Growth Promotion**
   Beyond the cycling and solubilization of nutrients, the microbiome performs several other key functions that support the growth of healthy plants. The production of phytohormones by many microbes can help regulate the plant's growth, development, and reproductive processes[10]. Likewise, mycorrhizal fungi establish symbiotic associations with plant roots that expand their effective subterranean surface area, allowing them to absorb more nutrients and moisture.

3. **Disease Regulation**
   The microbiome can fundamentally influence disease dynamics within ecosystems. Beneficial microbes can suppress harmful pathogens by out-competing them for space and resources, or by producing antimicrobial compounds and enzymes[11]. These products can be manufactured into biocontrol agents or seed treatments which are naturally degraded and do not form residues.

4. **Drought Tolerance**
   Certain soil microbes can increase an ecosystem's ability to tolerate low-moisture conditions. Exopolysaccharides (EPS) can recover soil structure in drought conditions through processes such as soil humification and aggregate formation, while mycorrhizal fungi networks allow for plants to access water from deeper soil layers when surface water availability is limited[12]. Furthermore, the process of microbe-mediated organic matter decomposition releases carbon compounds that contribute to the formation of stable soil aggregates and the creation of pore spaces, which in turn improve the soil's ability to retain water[13].

5. **Abiotic Stress Tolerance**
   Similarly, microbes can help combat the effects of saline soil on plants by secreting antioxidants and osmoprotectants that reduce overall salinity and can promote plant germination in saline conditions[14]. Additionally, many endophytes play key roles in phytoremediation, allowing plants to withstand higher concentrations of heavy metals within the soil[15].

Economic Outcomes of Healthy Microbiomes

Given the various crucial roles that the soil microbiome plays in supporting the agrarian ecosystem, the health of a microbial community plays a significant role in the system's ultimate output. Thus, promoting and maintaining healthy soil microbiomes in agriculture can yield significant economic advantages for companies across all aspects of business.

- **Yield Enhancement**
  Healthy soil microbiomes can enhance agricultural productivity by supporting nutrient cycling and plant growth in agroecosystems. This has been shown to increase crop yields dramatically, providing farmers with higher income and profitability[16]. The improved nutrient uptake supplied by microbes also reduces the need for chemical fertilizers, allowing farmers to save further costs[17]. Additionally, the microbes; ability to promote soil structure and water uptake by plant roots allows for more efficient irrigation practices on farms.

- **Stress Resistance**
  Beneficial microorganisms in healthy soils can allow crops to become more resistant to both biotic and abiotic stresses, including disease, drought, salinity, and toxic metals. This causes farms to incur fewer overall crop losses, further supporting crop yield and profitability. The enhancement of crop resilience also promotes a more stable supply chain, protecting businesses that rely on agricultural products from chain disruption and price volatility. This feature is especially relevant as climate variability and extreme weather events are becoming more frequent due to climate change.[18]

- **Environmental Health**
  The soil microbiome plays a vital role in maintaining environmental health through its varied contributions. Firstly, microbes in the soil help to sequester atmospheric carbon dioxide acting as a significant carbon sink that can aid in offsetting greenhouse gas emissions. This provides companies with numerous opportunities for financial gain through carbon offset markets and compliance with sustainability goals and regulations. Moreover, these practices can lead to consumer recognition for environmentally friendly and sustainable products. Furthermore, evidence is building that inorganic inputs such as NPK fertilizers can cause eutrophication where they run off land into both fresh and marine waterways requiring expensive cleanup operations.

	Microbial Mechanism	**Economic Outcome**
Yield Enhancement	Nutrient Mobilization Growth Promotion	Reduced Fertilizer Use Water Efficiency Increased Crop Yield
Stress Resistance	Disease Management Drought Tolerance Phytoremediation Salt Tolerance	Fewer crop losses Supply chain security Resilience to climate variability

Environmental Health	Soil Carbon Uptake	Consumer recognition
	Ecosystem Services	Market Premiums
	Nutritional density of produce	Carbon offsetting

It is important to consider that although evidence is building for the net positive role that the microbiome can play in these areas, there remain challenges associated with the high degree of complexity in the microbiome and multitude of microorganisms that have not been sequenced or characterized yet. There exist both good and bad microbes in every microbiome and unless their functions and ecological roles are fully understood, it will be difficult to know whether they are necessary for community stability (and therefore associated functions or services) or isolated components external to the agroecosystem. This level of intricacy creates issues in developing macroscopic changes to the microbiome that must be addressed as field-level microbial solutions become more prevalent.

4. Nature-Based Solutions for the Microbiome

Given the critical role of the microbiome within the agroecosystem and its scope of influence on natural capital within the industry, there is much to gain from employing nature-based solutions delivered by the microbiome to optimize productivity and improve sustainability. There are multiple ways of altering the structure and composition of the soil microbiome, including the informed adjustment of traditional practices, introduction of single or community microorganisms via inoculation, or the development of predictive analytics that integrate microbiome data into precision agriculture frameworks.[19] In the interpretation of microbiome data whether for baselines or during cultivation, it is important always to integrate metadata in the context of the crops and treatments to the soil in previous seasons and indeed perhaps even extending to previous years.

Solutions like these that focus on holistically nurturing soil health and microbiome biodiversity can play a significant role in stimulating growth, enhancing fertility, and developing stress tolerance in crops. By recognizing the environmental significance of factors like these, businesses can not only achieve long-term benefits of nature-based solutions but allow for sustainable agriculture practices to become more financially viable on large scales.

Nature-Based Solutions

Nature-Based Solutions (NBS) are approaches to ecosystem management that address societal and environmental challenges utilizing the natural world. These solutions are intended to work in harmony with ecosystems, harnessing their intrinsic benefits to provide sustainable and effective responses to environmental threats.[20] Nature-Based Solutions continue to gain prominence in modern industries as cost-effective, efficient ways to mitigate and adapt to the growing challenges posed by climate change.

Nature-Based Solutions for the soil microbiome involves strategies that support and sustain the native community of microbes that perform beneficial functions within the agroecosystem. By integrating the preservation and enhancement of the native microbiome into agricultural practices, farmers can effectively promote ecological resilience and environmental health while simultaneously reaping the economic benefits that healthy microbiomes provide.

The Impacts of Traditional Agricultural Practices on the Microbiome

Successful and sustainable microbiome solutions rely on a full understanding of the effects of traditional farming practices upon the microbiome. Common agricultural practices can significantly impact the structure and composition of the soil microbiome. By understanding these interactions, agricultural scientists can design microbiome engineering strategies that complement existing practices and learn to alter agricultural management procedures to account for microbial health[21].

- **Tillage**
  Tillage practices involve the mechanical turning of soil to manage weeds and pests. However, this process can be highly detrimental to the soil microbiome because of the physical disturbance and erosion caused by tilling the soil[22]. The disruption of soil structure can interfere with the formation of microbial aggregates and disrupt beneficial relationships within the microbial community. Moreover, some vulnerable populations of microbes, including highly-sensitive or anaerobic species, can be subject to loss because of the physical disturbances and aeration of soil, diminishing the overall microbial diversity.

- **Crop Rotation**
  The practice of crop rotation involves planting different species of crops in succession on the same piece of land. Each different crop brings a unique set of root exudates and supports different microbial communities, stimulating a diverse and dynamic soil microbiome[23]. Additionally, the rotation of crops with different nutrient requirements promotes a more balanced nutrient budget within the soil, allowing for increased nutrient cycling and more fertile soils.

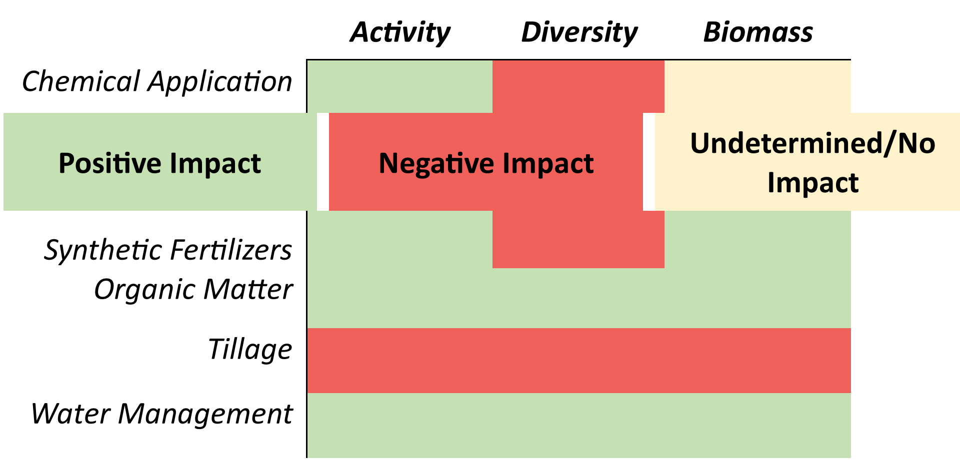
- **Appropriate Water Management**
  Adequate management of soil moisture content is essential to supporting the overall health of the microbiome. Sufficient water availability maintains a diverse range of microbial species, as most microorganisms require water to carry out fundamental biological processes. A balanced water supply has also been shown to drastically increase microbial activity and functional potential, allowing for processes like nutrient

cycling, organic matter decomposition and pathogen suppression to operate at optimal efficiency[24].

- **Chemical Application**
  The application of agrochemicals, such as herbicides and pesticides, can have extensive effects on the soil microbial communities. Although commonly used to control pests and weeds, their unintended toxicity to non-target organisms can disrupt microbial communities, interfering with beneficial microbe-microbe relationships and decreasing overall microbial diversity.

- **Synthetic Fertilizers**
  Applying synthetic fertilizers can supply the soil with high concentrations of nutrients over short periods of time, leading to the predominance of specific microbes that are specialized in utilizing the provided nutrients over other microbial species, decreasing microbial diversity. A sudden excess of nitrogen can have other detrimental effects on the soil and its native microbiome, including the suppression of mycorrhizal associations[25], the accumulation of organic matter, and development of soil acidification[26].

- **Organic Matter**
  The addition of organic matter to the soil is often done in agricultural settings to promote fertility and enhance nutrient availability to crops. Organic soil amendments can likewise enhance microbial diversity by providing many essential nutrients for soil microorganisms, as well as increasing microbial activity through the process of organic matter decomposition[27]. The increased microbial activity also contributes to the improvement of soil structure and the formation of stable soil aggregates, allowing for a healthier and more productive soil ecosystem.



The table above depicts a summary of the effects of the agricultural practices preciously described. With these general associations in mind, some broad recommendations for microbiome-positive practices include the utilization of:

1. **Low-Tillage Soil**
2. **Crop Rotation**
3. **Organic Amendments**
4. **Reduced Chemical Inputs**
5. **Appropriate Water Management**

Although these practices have demonstrated effectiveness at fostering symbiotic relationships in specific studies, their actual impacts are far more complex and contingent on several factors, including the local climate, microbial composition, and crop species. Therefore, the most effective microbiome solutions will adapt management practices to suit the unique needs of each site and be able to adjust dynamically according to real-time microbial and environmental data.

Precision Agriculture

One method of dynamic agricultural practice that is already widely implemented within the farming industry is precision agriculture. The term 'precision agriculture' refers to the use of technology to inform targeted agricultural management, including the application of chemicals and fertilizers as well as precise irrigation control, and has existed since the 1980s. According to a recent report by the United States department of Agriculture (USDA), 24% of US cropland utilized precision agriculture in 2019, with more recent studies suggesting that the number continues to rise[28]. Moreover, European nations such as Netherlands and Denmark continue to pioneer the technological advancements integral to the development of precision agriculture, while countries with large agricultural exports, such as Brazil and Argentina, have also been shown to benefit from the use of precision agriculture.

Precision agriculture, with its global reach and constantly evolving technology, thus presents an excellent opportunity to integrate microbiome data into existing agricultural systems. This integration can enhance the current infrastructure that already is being used to inform agricultural practices across the globe, utilizing microbial data to supplement other agricultural data. However, for microbial data to successfully integrated into precision agricultural structures, standard parameters for assessing microbial health must be established.

5. Science-Based Targets and Microbial Parameters

Science-Based Targets

The concept of science-based targets (SBTs) involves setting quantifiable goals informed by research for businesses to improve their sustainability and environmental responsibility. Although often used to address a company's greenhouse gas emissions, SBTs can be applied to any interactions that a business has with the natural world, including the soil microbiome. Adopting SBTs as a framework for effective environmental action can allow companies to gain multiple benefits, ranging from regulatory compliance to gaining an enhanced brand reputation as an environmentally responsible and socially conscious organization[29].

Science-Based Targets relating to the soil microbiome offer many additional financial and environmental benefits that provide structure for sustainable land management and regenerative agriculture.

- First, compliance with microbial SBTs ensures that agricultural practices align with the most up-to-date scientific knowledge, such that beneficial soil microbiome functions are optimized.
- Secondly, the ability of the microbiome to act as a carbon sink can also help agricultural companies with healthy soils to comply with SBTs related to emission reduction, which are more commonly implemented in modern industry.

However, much work is still necessary to define the ranges within which effective carbon sequestration can occur and be sustained, and to recognize whether the decomposition of microbiomes contributes to eventual release of greenhouse gasses into the atmosphere. Additionally, regular monitoring of the soil to assess target compliance would facilitate swift detection of any microbiome-related issues, allowing for quicker implementation of necessary solutions.

At the time of this report, science-based targets that are specifically tailored for the soil microbiome are an emerging concept that has yet to be widely implemented. Although there is a growing movement to address soil health and microbiome support in agriculture, the practice of setting SBTs specifically for the soil microbiome has not been commonly established. However, numerous major companies across a wide range of industries are currently adopting emission reducing SBTs[30], indicating growing precedent for the creation and usage of SBTs in business.

Microbial Parameters

Implementing SBTs related to the microbiome first requires the identification of microbial parameters that are both measurable and relevant to the health and agricultural productivity of the soil microbiome. Traditionally, soil health has been a loose term encompassed in physical and chemical characterization of soil types and properties. However, the living part of the soil, the microbial complement has rarely featured in commonly used health indices used.

A healthy microbiome is difficult to explicitly define, as microbial communities are made up of millions to billions of individual microbes both beneficial and harmful to the overall health of the ecosystem. In the context of constructing a sustainable and productive agroecosystem, microbial health will be defined by its agricultural efficiency – the ability to carry out the necessary ecological functions that stimulate and support crop growth.

Measuring the microbial health this way can be extremely complex, as there are many measurable microbial parameters that can influence agricultural productivity in ways that are not yet fully understood. However, there is a growing body of research linking agricultural output to specific microbial datapoints. Although the biological significance of any microbial parameter depends on the species of crop used and the nature of the agricultural environment studied, several key parameters have been identified across numerous studies as having substantial effects on the overall agricultural yield.

- **Microbial Diversity**
  The diversity and abundance of different microorganisms is essential for ecosystem stability and resilience. High microbial diversity can provide a wide variety of beneficial biological functions, as well as the ability to adapt to environmental changes. Diversity in the microbiome can be quantified using indices like Simpson's index or Shannon diversity. Numerous studies have documented the positive correlation between microbial diversity and agricultural output, as well as the negative impact of practices that reduce microbial diversity, such as tillage[31].

- **Carbon Utilization**
  Carbon utilization is the ability of microorganisms to utilize or decompose organic carbon sources in the soil, such as plant residues or root exudates. It is critical to the soil microbiome's function as it governs processes such as nutrient cycling and organic matter decomposition. Microbiomes containing effective carbon utilization profiles can efficiently release essential nutrients from complex organic compounds, supporting fertility and agricultural productivity. Commercially available microtiter plates are emerging methods for quantifying the carbon utilization profile of the soil.

- **Functional Gene Abundance**
  Functional gene abundance is the measurement of the quantity of genes that encode specific functional traits within the soil microbiome. Unlike diversity, which measures the abundance of different microbial species, functional gene abundance can provide insights into the microbial community's capability to carry out specific biochemical processes necessary to the ecosystem. Common microbial processes assessed using this method in agriculture include nitrogen fixation and organic matter decomposition. Functional Gene abundance is often measured using molecular biology techniques, particularly high-throughput DNA sequencing. Being able to triangulate functional gene abundance with data on metabolomics and proteomics will help to further elucidate not only gene functions but the relationships that metabolites and proteins have in functional terms.

- **F:B Ratio**
  The fungi (F) to bacteria (B) ratio is a fundamental metric that is used to quantify the relative abundance of fungi and bacteria in a soil microbial community[32]. While the F:B ratio provides valuable information on the structure and dynamics of its microbiome, there is no optimal operating ratio, as it is highly dependent on its environment and availability of nutrients. For instance, a high F:B is preferred low nutrient soils with high organic matter due to the ability of mycorrhizal fungi to break down complex organic

compounds, whereas a low F:B is preferred in high nutrient soils with low organic matter as bacteria have a higher capacity for mineralization.

Ultimately, there is no single parameter can provide definitive information about the health or growth potential of a given soil microbiome. Agricultural ecosystems are incredibly diverse and complex, often influenced by variable environmental factors such as soil type and climate. As such, developing concrete and implementable SBTs for the microbiome involves a full understanding of the intricate relationships between the established microbial parameters and the overarching agricultural ecosystem.

Recommended Science-Based Targets for Businesses

Using the quantifiable parameters established above, it is possible to set concrete numerical Science-Based Targets that can be implemented to fully take advantage of the microbiome's potential to enhance agricultural sustainability. While the specific numbers of the Science-Based Targets may vary from business to business, depending on the properties and environmental conditions of each individual agricultural system, SBTs remain a viable solution that can be applied to a wide range of businesses. Below are some recommended SBTs based on improvement trends rather than exact figures:

1. **Microbial Diversity Enhancement:** Set a target to increase the alpha (small-scale) and beta (large-scale) diversity of microorganisms in the soil microbiome by a given percentage. This could be achieved through practices such as crop rotation, reduced tillage, and organic matter incorporation, all of which promote the proliferation of diverse microbial communities and support nutrient cycling.

2. **Carbon Sequestration Optimization:** Establish a target to enhance carbon sequestration in the soil by increasing the abundance and activity of carbon-fixing microorganisms and mycorrhizal fungi. This can be achieved using microtiter plates to measure the carbon utilization of microorganisms.

3. **Nitrogen Use Efficiency:** Aim to improve nitrogen use efficiency in agricultural systems by optimizing the activities of nitrogen-fixing and nitrogen-transforming microorganisms. The F:B ratio, as well as the functional gene abundance for N-fixing bacteria is a useful metric in determining whether the soil microbiome is appropriately equipped to process the nitrogen in the soil and minimize nitrogen losses.

As our understanding of microbial data deepens, a more comprehensive barometer of soil health based upon microbiome signatures that account for a broad range of parameters can gradually be developed and refined. This will provide businesses with soil health SBTs that more accurately reflect the health of the soil, which can be exploited to drive regenerative systems and sustainability.

6. Integrated Microbiome Solutions

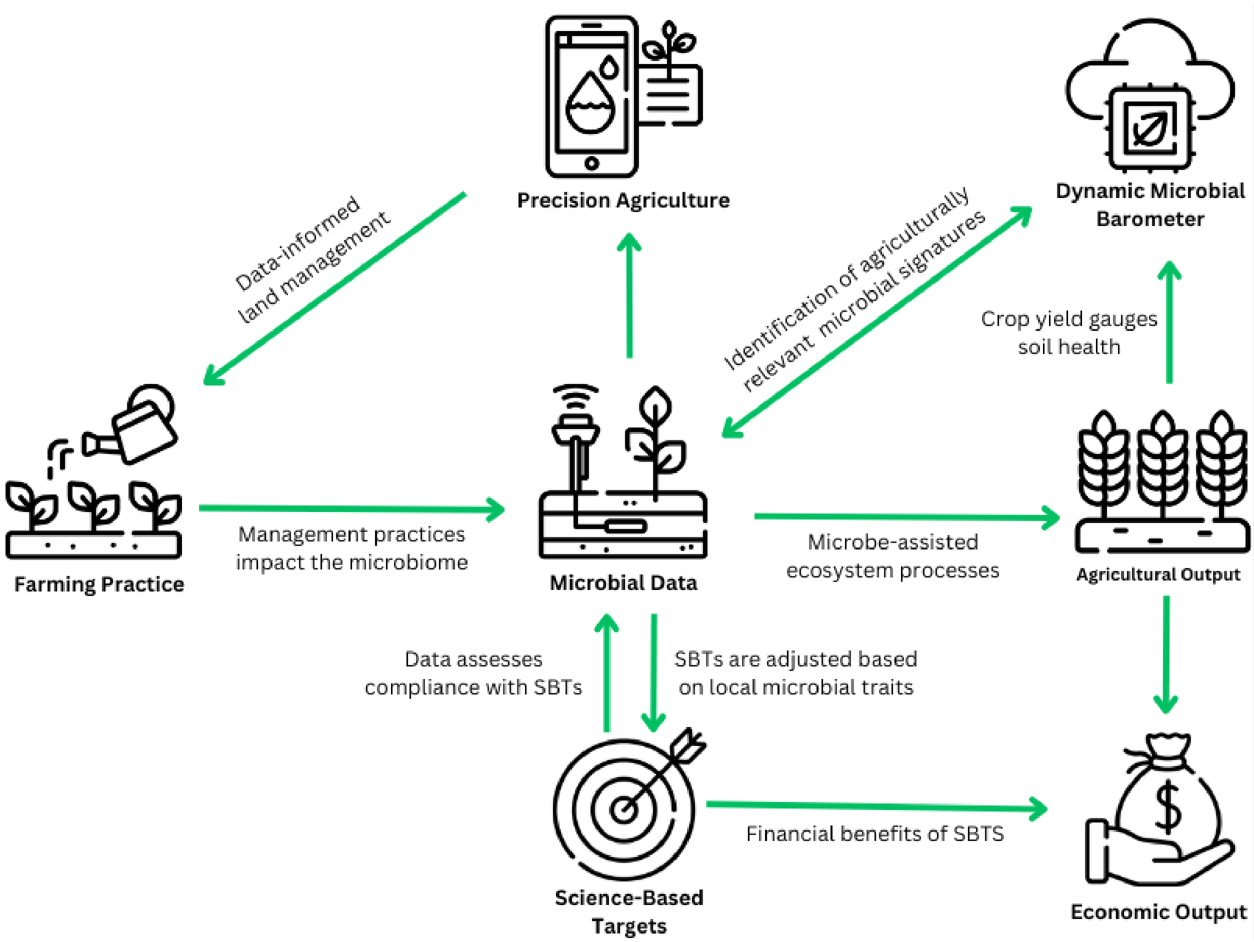
The key to harnessing the microbiome's potential to influence, enhance and drive more efficient ecosystem services in service of soil, plant, animal and human health as well as the health of the environment depends on the successful integration of microbiome data and technology into existing agricultural frameworks. Understanding the complex web of interactions between the soil microbiome, plant health, and the surrounding agricultural environment allows for the development of holistic solutions that simultaneously address the various threats facing global soil health.

Microbiome Monitoring

The first step in establishing integrated solutions for the microbiome is to construct viable frameworks for monitoring and analyzing microbiome health and function. Using previously established parameters such as microbial diversity, carbon utilization, and F:B ratio, farmers and researcheers can make informed judgements about the diversity, microbial makeup and abundance of microbes with their soils. Functional gene abundance, in particular, is crucial for its ability to assess the functional capabilities of the microbial community that directly control nutrient cycling, disease suppression, organic matter decomposition, and other critical processes[33]. However, it remains important to measure a range of parameters to get a holistic picture of the microbial activity taking place.

Utilizing established microbiome-specific markers across a range of both fertile and depleted soil samples can enable researchers to develop a profile of healthy microbiome indicators. This comprehensive approach involves the comparison of microbial and environmental data with agricultural output, facilitating the identification of specific combinations of microbial signatures that are correlated with agricultural outcomes. With increased adoption of microbial monitoring and the insights provided by network science, new microbiome samples can be integrated into a growing database, creating a dynamic microbial barometer to accurately gauge microbiome health.

Predictive Microbiome Analysis



Functional relationships between various components of integrated microbiome solutions[34]

Predictive Microbiome Analysis is a data-driven approach that seeks to elucidate the complex interactions between microbial communities and agricultural ecosystems[35]. By linking agricultural practices with quantifiable microbial patterns, increasingly called 'characters' or 'signatures,' predictive microbiome analysis allows for informed decision-making and improved resource management within agriculture. A successful integration of microbiome data within precision agriculture can revolutionize sustainable agriculture and harness the power of microbiome to support food security in the face of growing challenges. How this information can guide recommendations to estate owners and farmers still requires some development and the economics of these business models require further evolution.

A 2021 review of present and future microbial management strategies by French et al. made this statement on the potential for predictive microbiome management:

> *"Predictive microbiome management at field scale will require advances in computational approaches that can translate increasingly large amounts of microbiome data into data-driven decisions for managing all interconnected sectors of crop microbiomes, such as risk assessment, use of microbial indicators to identify stress or damage, and predictive modelling of microbiome spatiotemporal dynamics."* [36]

It is important to consider that modeling the microbiome in the digital space is a complex and multifaced endeavor. The ability of microbes to replicate rapidly means that the composition of microbiomes is dynamic, constantly adapting to environmental stressors. This complexity can be elucidated through the lens of network science, which helps unravel the intricate interactions within the soil microbial community. Analyzing functional relationships between microbes using network science is the key to developing realistic and applicable tools for precision microbe management.

7. Challenges and Barriers

Integrated microbiome solutions and microbial SBTs face several significant barriers to widespread implementation and acceptance. Addressing these challenges is necessary to ensure the long-term viability of microbiome solutions and unlock their full potential to enhance sustainable and resilient agriculture.

- **Knowledge Gap:** The complexities and dynamic nature of soil microbiomes are yet to be completely understood. While considerable progress has been made in analyzing microbial communities and their functions, their intrinsic functional diversity makes it difficult to diagnose specific cause-and-effect relationships. Moreover, although functional genes can be identified within specific microbes, there is a lack of certainty regarding which additional microbes are responsible for maintaining the fidelity of the function. It is essential that researchers aim to bridge this gap by conducting in-depth studies to unravel the nuances of microbial communities.

- **Variable Microbial Responses**: The structure and composition of different microbial communities within the soil are highly variable and influenced by numerous environmental factors, including climate, precipitation, and crop species. Widespread implementation of SBTs may require site-specific adjustments to account for the unique microbial characteristics of different agricultural settings.

- **Data Integration:** Integrating diverse data streams, including microbial, environmental, and ecological data presents a massive technological hurdle as datasets often differ in format, scale, and quality. Overcoming data integration challenges necessitates standardized data collection protocols and advanced approaches to data analytics.

Moreover, collaboration among farmers, researchers, and data scientists will be instrumental in promoting effective data sharing and analysis.

- **Consensus Building:** As a relatively novel concept in the agriculture industry, engaging stakeholders, including farmers, policymakers, researchers, and industry players is crucial for promoting awareness and buy-in for microbiome solutions and SBTs. Building a consensus around the importance and benefits of microbiome-focused targets solutions and targets is vital for successful implementation.

- **Technical Challenges:** Studying and monitoring the soil microbiome requires advanced molecular techniques and bioinformatics tools, which can be expensive and technically demanding. As such, limited access to microbiome data and technologies may hinder the widespread adoption of microbiome solutions. Thus, the financial benefits of adopting SBTs and microbial solutions must be made clear to incentivize the adoption of microbiome-oriented technology.

Regardless of how the various challenges present themselves in the process of agricultural innovation, it is crucial that all stakeholders, including financial entities, companies, farmers, and researchers, remain engaged and maintain transparent lines of communication. Cooperation and debate from all sectors will help promote fair and equitable solutions that embrace new technologies while maintaining a commitment to mutual success.

8. Concluding Remarks

The future of precision microbiome management holds a unique opportunity to usher in a new era of agricultural innovation and sustainability and an era of benefit for both farmers and estate managers, industry, and the environment. As the ecological understanding of soil microbiomes deepens and technology continues to advance, precision microbiome management moves closer to achieving tailored nature-based solutions and dynamic land management strategies. Both efforts strike a balance between food production that is healthy for consumption, and a restorative approach to the use of natural resources. Advancements in microbial sequencing, bioinformatics, and data science will enable a more comprehensive and detailed profiling of microbial communities within the soil. This wealth of data, coupled with innovative network science platforms, will empower researchers and farmers to unravel complex interactions between microorganisms, crops, and environmental factors.

The integration of real-time microbial monitoring systems that inform dynamic soil health barometers will provide continuous insights into microbial processes, enabling adaptive management practices that respond to changing conditions. Moreover, the integration of microbial data into existing precision agriculture systems will capitalize on the microbiome's potential to enhance nutrient availability, disease resistance, and stress tolerance within the agroecosystem. It will be necessary to build an appreciation of the contextual nature of these by crop, soil type and geography and understand which elements of these may be conserved across different contexts and which are likely to present advantages in specific contexts.

In this evolving landscape, precision microbiome management will be a cornerstone of future regenerative and sustainable agriculture. Farms will become data-driven ecosystems, where microbiome insights are seamlessly integrated into decision-making processes. Implementing precision microbiome management practices will optimize crop yield and quality, foster soil health, mitigate environmental impact, and enhance climate resilience. This data revolution will likewise enable the proliferation of science-based targets specific to the microbiome, providing further ecological and financial incentives for companies to strive for healthier soil microbiomes. Simultaneously, understanding what you have in your soil as a farmer will create opportunities in enabling a circular bioeconomy.

Collaborations between researchers, farmers, industries, and policymakers will be pivotal in driving the widespread adoption of these practices. As we harness the potential of microbiomes to shape agricultural landscapes, the future promises a unified combination of cutting-edge science, technology, and ecological wisdom, redefining the way we cultivate food and nurture the land.

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