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Ilex Paraguariensis Soil Sustainability Forestry Indicators in the Era of Biodiversity: A Case Study

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Abstract: *Soil microbial diversity plays a pivotal role in maintaining forest ecosystem health, contributing to nutrient cycling, disease suppression, and overall soil fertility. As the demand for sustainable forestry practices increases, especially in plantations like Ilex paraguariensis, there is a critical need to develop new indicators or integrate soil microbial indicators into forest management frameworks. This manuscript explores the potential of soil microbial diversity as a core component of sustainable forestry management with a focus on I. paraguariensis, proposing novel indicators and practices tailored to enhance and monitor microbial edaphic health. We review current methodologies for assessing soil microbial diversity, including molecular techniques such as DNA sequencing and functional profiling in the context of forestry. The manuscript further presents case studies from various forest ecosystems where microbial diversity management has been successfully implemented. In addition, we propose a set of practical guidelines for forest managers of I. paraguariensis plantations to incorporate microbial health indicators into their landscape management strategies. These guidelines emphasize the importance of maintaining organic matter inputs, minimizing soil disturbance, and promoting native plant diversity to support robust edaphic microbial communities. Finally, by bridging the gap between microbial ecology and forest management, this manuscript aims to provide a framework for enhancing soil health and sustainability in I. paraguariensis plantations through the lens of microbial diversity.*

1. Soil Microbial Diversity and Its Ecological Functions

Soil microbial diversity encompasses the vast array of bacteria, fungi, archaea, and other microorganisms residing in the soil, forming an essential component of terrestrial ecosystems. These microorganisms are integral to numerous ecological processes maintaining soil health and fertility by driving nutrient cycling, organic matter decomposition, and soil structure formation (Bardgett & van der Putten, 2014). The diversity of soil microbes is not merely a reflection of species richness but also of functional diversity, where different microbial taxa contribute to varied biochemical processes essential for the functioning of every ecosystem and their sustainability (Coleman & Whitman, 2005).

Bacteria and fungi decompose organic matter, releasing nutrients such as nitrogen, phosphorus, and sulfur, which are vital for plant growth (Boer et al., 2005; Smith & Read, 2008). Specific groups of microbes, like nitrogen-fixing bacteria (e.g., *Rhizobium* species) and mycorrhizal fungi, establish symbiotic relationships with plants, enhancing nutrient uptake and improving plant health and productivity (Hoorman, 2011; Wall et al., 2015; Onetto et al., 2022; Cortese et al., 2023). This nutrient cycling capability underscores the importance of maintaining a diverse microbial community to support forest ecosystems.

In addition to nutrient cycling, soil microorganisms play a crucial role in disease suppression and soil pathogen regulation. Beneficial microbes, such as certain species of *Bacillus* and *Trichoderma*, produce antibiotics and antifungal compounds that inhibit pathogenic organisms, thereby protecting plant health (Compant et al., 2005; Vinale et al., 2014; Pedrozo et al., 2023; Swathy et al., 2024). By maintaining a healthy and diverse microbial population, forest soils can resist forestry disease outbreaks and support resilient forest ecosystems (Borowik et al., 2022).

Soil structure and fertility are also profoundly influenced by microbial activity. Microbes contribute to the formation of soil aggregates, which enhance soil porosity and water retention capabilities (Chotte, 2005). Fungal hyphae, in particular, create extensive networks that bind soil particles together, improving soil stability and aeration (Hoorman, 2011). These physical changes to the soil environment facilitate root penetration and growth, directly impacting plant health and forest productivity (Bot & Benites, 2005). Thus, the physical and chemical modifications driven by soil microorganisms are fundamental to sustaining forest soil health.

The interactions between soil microbes and forest vegetation form a complex web of ecological relationships that underpin forest ecosystem functioning. Plant root exudates provide a carbon source for soil microbes, influencing microbial community composition and activity (Bardgett & van der Putten, 2014). In turn, soil microbes affect plant growth and health through nutrient provisioning and disease suppression. This reciprocal relationship highlights the need to consider microbial diversity in any forest management practices, especially in those plantations exposed to a continuous biomass extractive process, as is the case of *I. paraguariensis*. Studing, recognizing and fostering these interactions can lead to more sustainable and productive forestry practices (Bender et al., 2016).As research continues to uncover the depths of microbial contributions to soil health, integrating microbial indicators into forestry practices becomes increasingly imperative for fostering resilient and sustainable forest ecosystems (Wall et al., 2015; Bardgett & van der Putten, 2014).

2. CURRENT INDICATORS OF MICROBIAL HEALTH IN FORESTRY SOILS

Indicators of microbial health in forestry soils are essential for assessing and managing soil quality and sustainability. These indicators can be broadly categorized into biological, chemical, and functional indicators. They provide insights into the diversity, abundance, and activity of soil microorganisms, reflecting the overall health of the soil ecosystem. Effective indicators help forest managers make informed decisions to maintain or improve soil health and plantation productivity.

2.1. Biological Indicators

Biological indicators include measures of microbial biomass, diversity, and community structure. Microbial biomass, often assessed through soil respiration or microbial biomass carbon, indicates the total mass of microorganisms in the soil and provides a general measure of microbial activity and potential for nutrient cycling (Jenkinson & Ladd, 1981; Böhme et al., 2005 Das et al., 2023). Microbial diversity, typically assessed using microbiological techniques, provides information about the composition of some microbial communities and their potential functions. Now, advancements in molecular biology have enabled the use of genomic approaches to assess microbial diversity of soils. Techniques such as metagenomics provide comprehensive insights into the genetic potential and functional activity of soil microbial communities (Daniel, 2005; Frey et al., 2022). These approaches allow for the identification of key microbial taxa and functional genes involved in critical soil processes, offering a detailed understanding of microbial functions and their responses to environmental changes (Ma et al., 2021). High microbial diversity is generally associated with greater ecosystem resilience and stability (Wagg et al., 2014).

2.2. Chemical Indicators

Chemical indicators include measures of soil organic matter, nutrient levels, and soil pH, which are critical for microbial health. Soil organic matter serves as a primary energy source for microorganisms and is crucial for maintaining microbial activity and diversity (Six et al., 2002). Nutrient levels, particularly nitrogen, phosphorus, and potassium, are vital for microbial metabolism and growth (Paul, 2007). Soil pH affects microbial community composition and function, with different microbes thriving in different pH ranges (Rousk et al., 2010). Monitoring these chemical properties helps in understanding the conditions that support or hinder microbial health.

2.3. Functional Indicators

Functional indicators measure the biochemical processes carried out by soil microorganisms, such as enzyme activities and nutrient mineralization rates. Enzyme activities, such as those of phosphatases, cellulases, and proteases, indicate the potential for organic matter decomposition and nutrient cycling in the soil (Weintraub et al., 2013). These functional indicators are direct measures of the ecological functions performed by soil microbes and are critical for assessing soil health and sustainability (Kooch et al., 2021).

2.4. Integrative Approaches

Integrative approaches combine multiple indicators to provide a holistic assessment of soil microbial health. By integrating biological, chemical, and functional indicators, researchers can develop composite indices that reflect overall soil health and sustainability (Muñoz-Rojas, 2018). These integrative indicators are useful for forest land use designers, as they provide a comprehensive view of the soil ecosystem's status and its ability to support forest productivity and resilience. Such approaches also help identify the interactions between soil properties and microbial communities, leading to more effective management strategies (Duru et al., 2015).

3. Case Studies of Microbial Diversity Management in Tropical Rainforests

Tropical rainforests with high biodiversity and rapid nutrient cycling rely heavily on microbial processes. Broad deforestation and its subsequent poor-planned land-use changes can severely impact soil microbial diversity. A study by Berkelmann, et al. (2018) in the Indonesian rainforest found that converting rainforest to agricultural land significantly reduced microbial diversity and altered community composition. The decrease in diversity was attributed to changes in soil characteristics deriving from rainforest conversion and management. This underscores the importance of sustainable land-use practices that maintain microbial health in tropical ecosystems (Berkelmann et al., 2018; Rodrigues et al., 2012).

Some agroforestry systems, which combine trees with crops, have been shown to enhance soil microbial diversity in tropical rainforests. In a study conducted by Vallejo et al. (2010) in Colombia, agroforestry practices improved soil microbial activity and biomass compared to conventional monoculture systems. Agroforestry systems increased organic matter inputs through leaf litter and root exudates, creating a more favorable environment for diverse microbial communities. This approach not only supports microbial diversity but also could enhance nutrient cycling and soil fertility, contributing to more sustainable agricultural practices in tropical regions (Schroth & Sinclair, 2003; Dantas et al., 2014).

3.1 Microbial Biodiversity of Soil in *Ilex Paraguariensis* Plantations

Ilex paraguariensis, commonly known as yerba mate, is cultivated extensively in South America. Some studies have shown that the diversity and activity of soil microbes in yerba mate plantations can be influenced by various agricultural practices. For instance, studies conducted by Parron et al. (2024) indicated that alternative management practices based on *I. paraguariensis*, including agroecological agroforestry management, support higher microbial activity compared with conventional monoculture yerba mate production system. Reduced-tillage practices minimize soil disturbance, which helps maintain soil structure and microbial habitats, and promotes a stable and diverse microbial community (Cerecetto et al., 2021; Khan et al., 2023).

In general, agroforestry systems, which incorporate trees into agricultural landscapes, have been shown to benefit soil microbial diversity in yerba mate plantations. But interestingly, a study by Bergottini et al. (2017) evaluated by high throughput sequencing the effects of different historical agricultural management practices with yerba mate cultivation on its root-associated microbiome. The findings revealed that in most samples the agroforestry systems presented a similar alpha diversity, for both bacterial and fungal communities, with monoculture or *I. paraguariensis* co-cultivated with few tree species. These authors also found that the bacterial community of one plantation of yerba mate with an agroforestry system with native trees had a higher alpha diversity when compared to other agricultural management practices.

4. Proposed Practices for Monitoring and Enhancing Soil Microbial Health

Establishing comprehensive baseline data through soil testing is crucial to monitoring and enhancing soil microbial health. Baseline assessments should include measurements of microbial biomass, diversity, and community composition using methods such as DNA sequencing, and soil respiration tests (Vance et al., 1987; Fierer et al., 2007; Catania et al., 2022). Regular monitoring of these parameters allows for the detection of changes over time and the identification of potential issues early. Establishing a baseline helps forest managers to understand the initial state of microbial communities and to evaluate the effectiveness of implemented management practices (Rousk et al., 2010; Sharma et al., 2010).

Using cover crops is an effective method for enhancing soil microbial diversity and function. Cover crops, such as legumes and grasses, provide continuous organic matter input and protect the soil from erosion, fostering a more hospitable environment for soil microbes (Stagnari et al., 2017). These practices contribute to improved nutrient cycling and soil structure, enhancing overall soil health.

Applying biochar and other soil amendments can significantly enhance soil microbial health. Biochar, a form of charcoal produced from organic materialshas been shown to increase microbial biomass and diversity by providing a stable habitat and improving soil physical properties (Lehmann et al., 2011). Other amendments, such as mycorrhizal inoculants and microbial consortia, can be introduced to boost beneficial microbial populations and enhance nutrient uptake by plants (Van Der Heijden et al., 2008; Smith & Read, 2008). Some advances have been evaluated by Onetto et al. (2022) and Cortese et al. (2023) with microbial inoculants in *I. paraguariensis* which enhance its growth. These amendments may help to create a more favorable soil environment for microbial activity and diversity.

In summary, effective monitoring and enhancement of soil microbial health in tropical agronomic modified forests and in *Ilex paraguariensis* plantations involve comprehensive soil testing, the adoption of organic and reduced-tillage practices, the use of cover crops and biochar application as other site-specific organic developed soil amendments. These strategies may promote a diverse and active microbial community, essential for maintaining soil health and sustainability in tropical forest ecosystems especially in *I. paraguariensis* plantations.

5. Conclusion

In summary, the edaphic microbial diversity in tropical forestry systems, including *Ilex paraguariensis* plantations, is a central concern when maintaining ecosystem health and sustainability. Microbial communities contribute to nutrient cycling, soil structure formation, and disease suppression, all of which are vital for the productivity and resilience of forest ecosystems. Studies have shown that sustainable practices, such as organic management, use of biochar and other organic site-specific soil amendments, reduced tillage, and the integration of agroforestry systems, could enhance microbial diversity and activity, promoting overall tropical soil health. The case studies from tropical rainforests emphasize the significant impact of land-use changes, agroforestry systems, and reforestation on soil microbial communities. Sustainable management practices that maintain tree cover, use native species, and minimize soil disturbance are essential for supporting microbial health. Forest managers can cultivate resilient and productive ecosystems that promote biodiversity and sustainable forestry by embracing these practices and consistently monitoring microbial indicators incorporated into systemic indexes.

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