Journal of Science Research International (JSRI)
ISSN: 2456-6365 (Online)

OPEN ACCESS

EFFECT OF TREE SPECIES COMPOSITION ON SOIL MICROBIAL DYNAMICS

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Received: 10 February 2026	Revised: 12 April 2026	Accepted: 28 April 2026	Published: 22 May 2026

DOI: https://doi.org/10.5281/zenodo.20343709

Abstract:

Soil microbial communities are essential for nutrient cycling, breaking down of organic matter and maintaining of our terrestrial ecosystems. Multiple types of evidences have shown that these types of tree species present significantly influence soil microbial activity through changes in litter input, root exudation and microhabitat conditions. This review brings together recent studies to clarify how different types of tree species and their combinations affect the soil microbial diversity, activity and their function. Mixed-species plantations consistently show greater microbial richness and community resilience as compare to monocultures. This difference arises from variations in leaf litter chemistry, mycorrhizal relationships and strategies for nutrient uptake. As an illustration, different tree species, such as deciduous and evergreen trees, have different effects on microbial functional groups, especially with regard to nitrogen and carbon cycles. Additionally, environmental variables such as altitude and change in land-use can also play a role in these tree-microbial interactions. As indicated in the literature, these interactions are complex and contextual, emphasizing the need to consider the microbiome when managing forests. In essence, this knowledge is useful in promotion of biodiversity conservation, carbon sequestration and soil health improvement in forests.

Keywords: *Litter, Microbial Richness, Tree-Microbe, Forest Management.*

1. Introduction

Soil microbial communities are critical to how forest ecosystems function, supporting important processes like nutrient cycling, soil structure formation and breaking down organic matter [1,2]. These microbial groups are dynamic and respond to both living and as well as non-living factors, with the composition of vegetation-especially the types and diversity of tree species-being a major driver [3,4,5]. Forests dominated by specific tree species display unique microbial profiles by reflecting variations in root structure, exudation patterns, litter chemistry and canopy designing [6,7,5]. Recent studies emphasize the subtle impacts of tree species type, their richness and lineage on the structure and function of soil microbial communities [8,9]. For instance, deciduous angiosperms and evergreen gymnosperms influences microbial diversity, enzyme activity and nutrient dynamics differently [10,11]. Compared to monocultures, mixed-species forests tend to enhance microbial carbon use efficiency and support multiple functions [12,13]. Moreover, specific mycorrhizal associations tied to tree species play an important role in shaping the microbial community structure and nutrient dynamics [14,5]. Moreover, specific mycorrhizal associations tied to tree species play an important role in shaping the microbial community structure and nutrient dynamics [14,5].

The relationship between tree species and microbial communities varies across different spatial and temporal scales. Factors such as microclimate conditions, soil properties and human activities (anthropological) like land use changes add complexity to this relationship [11,15]. Understanding of how these tree species composition impacts the microbial dynamics is crucial for the effective forest management, ecological restoration and addressing climate change. This review aims to bring together recent findings to thoroughly examine how tree species composition-considering type, diversity and lineage-shapes soil microbial diversity, structure and function. By combining various pieces of evidence, this review paper helps to shed light on belowground biodiversity in forest ecosystems.

2. Tree species identity and microbial community composition

The species of tree is another factor that influences the soil microbiota. Tree species contribute to soil microbiota because they determine the quality of soil litter, soil roots, and nutrient uptake process. This influences the diversity of soil microbiomes [3,4]. For example, from the findings of the study by Chen *et al.* [16], there is a significant difference in the bacterial communities of soils that grow under *P. massoniana* and *Q. acutissima* due to the difference in the pH level, carbon, and nitrogen in relation to the type of litter produced by trees. The tree species' functional traits influence the dynamics of microbes via carbon and nitrogen availability. For example, tree species with ectomycorrhizae form different types of microbes compared to tree species with arbuscular mycorrhizae [7]. Different tree species such as *J. nigra* and *Q. rubra* have unique microbial species due to secondary metabolites and phenols [17]. However, there is evidence that evergreen and deciduous trees impact microorganisms differently. According to Augusto *et al.* [6], evergreen gymnosperm plants form more resistant litter, which is related to slower decomposition and different microbial communities in contrast with deciduous angiosperms. The same was confirmed by Zhang *et al.* [18], who found greater diversity and structure of microbial communities for mixed species plantations of *Castanopsis hystrix* compared to monoculture stands. Furthermore, the role of tree species can be revealed in microbial function patterns. As reported by Bowen *et al.* [19] the abundance and activity of denitrifiers is associated with plant species, implying a possible role of trees in nitrogen cycling. Tree-specific root exudates can serve as signaling factors controlling microbial recruitment and community composition [20]. Overall, such research provides proof that tree species plays an active leadership role in belowground diversity. Although there might be other drivers affecting the effect in question, tree species always demonstrate a certain effect on the richness, structure, and enzyme activity of microbial communities.

Apart from tree species themselves, the abundance of tree species diversity, or the diversity of tree species in an ecosystem, is also another key factor influencing soil microbial diversity. The more diverse tree communities present, the higher the chances of creating different ecologies and organic matter through increased microbial diversity [8,11]. For example, Duan *et al.* [8] discovered that greater tree species diversity enhanced microbial

CUE, providing insights into how microbes contribute to carbon retention in soils. Diverse forest ecosystems produce a greater diversity of litter, fostering the development of microbial groups with varying decomposition capacities. This additional diversity in organic matter leads to an increase in microbial diversity and enzyme activity in turn, promoting faster nutrient cycling rates in the soils [12,21].

In the subtropical forests of China, Chen *et al.* [4] found that microbial richness correlated more closely with species identity than with the overall number of species, but mixtures of broadleaves and conifers still showed greater microbial diversity than monocultures. Likewise, research by [10] and [17] indicated that mixed-species plantations curtailed fast-growing, opportunistic bacterial populations, promoting slower-growing groups linked to carbon stabilization. Eisenhauer *et al.* [11] pointed out that interactions among trees, such as competition and support, can indirectly shape microbial dynamics by altering microclimate, litter makeup and root overlap. In addition, microbial diversity in richer forest areas showed greater resilience to disturbances like nutrient enrichment or drought, suggesting that plant diversity helps stabilize microbial communities [22,3,5]. However, the connection between tree species richness and microbial diversity is not always straightforward or positive response. Some studies note a threshold beyond which adding more species does not significantly enhance microbial functions [10,7,5]. It indicates that composition and functional traits of tree species may be as important, if not more so, than total number of species. In conclusion, while tree species richness greatly impacts microbial diversity and ecosystem functions; outcomes are heavily influenced by species identity, resource use complementarity and functional characteristics. Effective forest management should thus prioritize not just diversity but also the thoughtful selection of species with complementary ecological roles [10,7,5]. It indicates that both composition and functional traits of tree species may be as important, if not more so, than total number of species. In conclusion, while tree species richness greatly impacts microbial diversity and ecosystem functions; outcomes are heavily influenced by species identity, resource use complementarity and functional characteristics. Effective forest management should thus prioritize not just diversity but also the thoughtful selection of species with complementary ecological roles.

3. Mycorrhizal symbioses are central to tree-microbe-soil interactions

These mutualistic relationships affect how trees acquire nutrients, suppress pathogens and build soil structure, all of which influence microbial community composition [3,7,5]. The two main types of mycorrhizae-ectomycorrhizal (ECM) and arbuscular mycorrhizal (AM)-differ in their ecological strategies and nutrient gathering abilities, leading to varying effects on soil microbial diversity. Tree species like *Fagus sylvatica* and *Quercus* spp. often associate with ECM fungi, promoting microbial communities that favour organic nitrogen use and slower decomposition processes [14,7]. In contrast, AM-associated species such as *Acer* and *Ulmus* generally promote microbial groups involved in phosphorus mobilization and quick nutrient cycling. Root exudates, which contain sugars, amino acids and secondary metabolites, further influence microbial colonization and activity. Wu *et al.* [20] highlighted that root exudation patterns vary significantly across tree species by impacting the microbial community in the rhizosphere. These exudates act as both energy sources and chemical signals thus fostering specific microbial partnerships.

Gao *et al.* [23] observed distinct responses of microorganism communities to N deposition depending on the predominant tree species, suggesting that the traits of roots and nutrient uptake efficiency might play a critical role in response to microorganism communities. Frene *et al.* [17] proved that the input of carbon through roots was different in trees like *Juglans nigra* and *Quercus rubra*. The presence of mycorrhiza is often considered “wood wide web” that contributes greatly to intercommunication of nutrients and formation of hotspots of microorganisms near root tips [12,24]. Thus, examples show the complexity of interactions within a triangle of tree-root-microbe in the soil of forests. Considering the importance of mycorrhiza, they must be accounted for while developing plans of forest biodiversity. Planting tree species with compatible types of mycorrhiza could result in higher microbial diversity, efficient nutrient cycling, and overall resilience of the system [17,5]. The understanding of the interaction of roots with microorganisms creates a firm basis for sustainable forestry and ecological restoration as well.

4. Influence of Litter Quality and Decomposition Pathways

Quality of tree litter is one of the most important factors that regulate the activities of microorganisms in the soils and shape their diversity. Tree litter is different in C:N ratio, amount of lignin, and nutrients. The effect on decomposition speed and the processes of successions in soil microbes vary according to tree species. Litter produced by evergreen species is characterized by low quality with high amounts of lignin and secondary metabolites, which stimulates fungal-dominated decomposition communities with slow rate [6,11]. Deciduous species produce high-quality litter, which favors fast colonization of bacteria and mineralization of nutrients [12,3,5]. According to Du *et al.* [25], tree phylogenetic relationships and litter quality had significant effects on extracellular enzymes responsible for lignin and cellulose decomposition. These processes are necessary for nutrient recycling and carbon sequestration. Litter diversity caused by the coexistence of several tree species in forest increases microbial diversity and stimulates complementary activity.

Jing *et al.* [15] have found out that different amounts of microbial residues or by-products of decomposition occur due to differences in tree types. This influences soil aggregate stability and organic matter preservation, establishing an association between the input of tree litter and soil carbon dynamics. At the early stages of degradation, fungi often predominate as litter is rich in lignin. Nevertheless, bacteria increase in abundance due to substrate availability [1,3,5]. There is a succession pattern determined by the specific tree species studied in the context of *Castanopsis*, *Eucalyptus* and *Cunninghamia lanceolata* plantations [18,26]. The interaction between the litter and soil fauna can affect the availability of the substrate for microbial life. Such factors as the shape of leaves, presence of waxes and VOCs contribute to colonization [27]. Thus, decomposition of tree litter is a process that occurs in species-dependent manner. It defines the composition and activities of microbes during decomposition. Therefore, managing litter of different plants will enhance decomposition processes and microbial diversity.

5. Environmental Moderators and Land-Use History

Even though the composition of the tree species strongly influences the activity of soil microbes, it may be affected by some other variables, which include topography, climate, land use, and soil characteristics. These moderating variables either amplify or suppress the effect of the vegetation on the activity of soil microorganisms, resulting in a variety of outcomes depending on the spatial-temporal conditions [4,28,5]. For instance, an increase in the altitude gradient could modify the structure of the soil microbial community due to changes in the soil water content, temperature, and vegetation type [4]. The rhizospheric soil microbiome on the Tibetan Plateau was highly variable at various altitudes and correlated with vegetation dominance. Likewise, Gao *et al.* [23] discovered that the microbial richness in coastal protection forests with varied tree species was influenced by the salinity level and soil pH.

The history of land use is another factor that determines the influence of previous plant vegetation on the microbial community. According to Jian *et al.* [29], microbial communities that transition from farm areas to forested sites vary on a species-specific basis, even within a relatively short period. As such, microbial recovery and soil biogeochemical functions are determined not only by the type of trees introduced to the land but also by the history of land use. Other soil properties that affect microbial communities include pH, bulk density, nutrients, and organic carbon. Gao *et al.* [23] discovered that changes in microbial communities brought about by nitrogen deposition vary according to the type of tree and soil characteristics.

Restorations using mixed-species plantations have been found to differ in microbial results based on degradation levels and disturbance regimes [29]. According to Xu *et al.* [30], mixed plantations, when not even-aged, helped restore aggregate functions of soil better than did pure plantations, indicating the influence that management practices can have on the microbial community by way of soil recovery. Besides, microhabitat differences, such as under-tree variations and litter depth, are capable of creating spatial niches that negate any influence that wider tree variety has on microbial populations [1,2]. It is clear that biotic and abiotic variables must be considered in conjunction. Environmental mediators play an important role in the tree-soil-microbe system. It is critical to learn about their interactions in order to better manage forest restoration, monitor soil condition and microbial contributions to ecosystem services.

6. Discussion

The species composition of trees acts as a rather complicated factor in the influence on the soil microbiota. Apart from including or excluding some species in a given area, this factor includes traits and interactions between trees and mycorrhizal fungi and also other environmental variables. The research findings reviewed above demonstrate the vital part played by plant-microbe interactions in shaping the functionality of forests and enhancing their resilience to various factors. Species identity has been found to be one of the factors contributing significantly to the composition of microbiota in ecosystems. Chemical and physical features of litter, root exudation, and canopies create particular conditions affecting selection and successions of microorganisms [3,7]. Thus, evergreen trees such as *Pinus* foster a community of microorganisms adjusted to the conditions of low nutrients and slow decomposition while deciduous ones like *Quercus* and *Castanopsis* favor rapid decomposition and bacteria [18,15]. Species richness of trees increases complexity even further. Species richness enhances microbial functional diversity and flexibility through the availability of multiple substrates as well as the inhibition of dominant microbial taxa due to competition [12,8]. Nevertheless, numerous empirical studies have shown that at a certain richness, the marginal utility starts to decline, leading to the emergence of functional redundancies [3,11]. Hence, optimal tree composition with regard to functionality requires functional complementarity rather than richness.

Associations of the plant with mycorrhiza, particularly the distinction between AM and ECM fungi, add another set of filters on the microbe. Symbiosis assists with nutrients uptake and shapes the microbial communities through root exudates and fungal mycelium networks. Plant species associated with ECM fungi foster fungus-mediated pathways of mineralization and decomposition, whereas those that form AM stimulate the activity of bacteria [14,24,5]. Tree community management can be helpful in optimizing nutrient use and disease prevention.

It has been known for some time that litter quality is related to decomposition. Litter with high lignin content and high C:N ratio causes slowed down decomposition rates and supports fungal populations, whereas easily decomposable litter increases bacterial activities and speeds up nutrient cycling [25,12,5]. Crucially, microbial residues resulting from decomposition are responsible for carbon stabilization in soils, thus the choice of tree species influences the microbial composition and amount of carbon stored in soil [10,31]. These relationships, however, are subject to other influencing factors such as elevation, climate, land use, and soil pH, which impact greatly the response of microorganisms to tree species [4,29].

Conclusion

The importance of the role of the species of trees in determining the soil microbial dynamics has been highlighted in this paper. The characteristics, number, and properties of different tree species-including mycorrhizae and litter quality-are key factors shaping the soil microbiology in various ways. The latter include root exudation, the formation of specific microclimates in the canopies, and differences in the decomposition of the litters. The studies show that more complex communities of microorganisms are usually found in the heterogeneous plantations rather than in monocultures because of the greater variety of niches created by diverse plant species. Nonetheless, the effects do not have the same impact in all settings. Variables such as altitude, soil conditions, previous land use practices, and nitrogen deposition play significant roles in how the interaction between trees and microbes is influenced by trees. In this case, a systems perspective should be applied to forest management in light of the biotic and abiotic elements that must be considered. Through careful consideration of the type of composition of the forest based on ecology, forests can be sustainably developed using microbial mechanisms.

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