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Advance Influence of Forest Biodiversity on Ecosystem Multifunctionality

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Abstract. Ecosystem multifunctionality (EMF) – the capacity of a forest to provide multiple functions simultaneously (e.g. biomass production, carbon storage, nutrient cycling) – is governed by diverse facets of biodiversity. Recent work shows that not only species richness but also functional diversity (FD), phylogenetic diversity, and structural complexity influence EMF. For example, tree functional diversity drives productivity via niche complementarity and dominance effects, and cascades to other trophic levels by providing more varied resources to herbivores and decomposers. Studies in subtropical forests have found that functional trait diversity often predicts multifunctionality more strongly than taxonomic richness. Likewise, tree species mixtures generally enhance multifunctionality compared to monospecific stands, with mixed broadleaf–conifer plantations showing especially high multifunctionality. Crucially, structural diversity – e.g. heterogeneity in tree size and canopy layers – has been identified as a dominant factor. Variation in DBH (diameter) was the strongest positive predictor of forest EMF, more so than species diversity or trait diversity. Belowground biodiversity also plays a key role: soil organisms (mycorrhizal fungi, nematodes, bacteria) mediate nutrient and carbon processes and can transmit aboveground diversity effects through trophic interactions. Conversely, anthropogenic disturbances (e.g. logging, fragmentation) can undermine EMF by reducing soil moisture and altering diversity patterns. For instance, human disturbance lowered soil moisture and thereby diminished the positive impact of biodiversity on multifunctionality in temperate forests. In sum, preserving and restoring multiple dimensions of forest biodiversity – taxonomic, functional, phylogenetic, and structural – is essential for sustaining ecosystem multifunctionality in natural and managed forests.

Keywords: forest biodiversity, ecosystem multifunctionality, functional diversity, structural complexity, phylogenetic diversity

1. Introduction

Forests deliver myriad ecosystem functions simultaneously (production, carbon sequestration, nutrient cycling, etc.), collectively termed ecosystem multifunctionality (EMF). Maintaining high EMF is critical for ecological resilience and ecosystem service provision. Biodiversity underlies EMF: many studies have documented positive links between plant diversity and individual ecosystem functions, and recent syntheses focus on multifunctionality across multiple processes [1].

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Biodiversity itself is multifaceted: it includes taxonomic diversity (species richness), functional diversity (the range of species' trait values), phylogenetic diversity (evolutionary history among species), and structural diversity (vertical and spatial heterogeneity of forests). These dimensions often covary but can have distinct effects on EMF. For example, high functional diversity can enhance niche complementarity, while structural diversity (e.g. canopy layering or variation in tree size) can improve light and nutrient exploitation. In addition, belowground diversity (microbes, soil fauna) and ecosystem context (climate, topography) modulate these effects. This review synthesizes recent findings on how forest biodiversity in its various forms influences EMF, with emphasis on empirical results from forests.

2. Taxonomic (species) diversity and multifunctionality

Numerous studies show that increasing tree species richness in a stand can enhance certain ecosystem functions, especially carbon storage and productivity. For instance, Shi et al. [2] reported that soil carbon stocks and overall multifunctionality rose significantly with tree species richness in a subtropical forest, whereas effects on nutrient cycling, decomposition, and productivity were weak [2]. Mixed-species forest plantations generally outperform monospecific stands: Li et al. [3] found significantly higher multifunctionality in mixed broadleaf–conifer plantations than in corresponding monocultures [3]. The magnitude of mixture effects depends on species identities; Li et al. [3] showed that mixing Cunninghamia lanceolata with broadleaf species increased multifunctionality by 36–87%, far more than mixing with other conifers (2–9%). Conservation scientists also emphasized that planted forests with diversified functions are more flexible and productive than single crops [4]. In summary, there is evidence that taxonomic diversity increases the EMF of many forests, although its effects may be asymptotic and may vary from function to function. It is important to note that species diversity often interacts with abiotic conditions: Zhao et al. [5] showed that human-induced soil drying limits the positive effect of biodiversity on the multifunctionality of mature temperate zones.

3. Functional trait diversity

Functional diversity (FD) refers to the scope and distribution of functional characteristics of species - such as leaf area, height, rooting depth and wood density - which determine how communities acquire resources and maintain ecosystems. In terms of ecology, FD has been established as a more powerful predictor of ecosystem multifunctionality (EMF), not just species richness. How organisms obtain, store and circulate energy and nutrients usually depend on their characteristics [6]. For example, Ouyang et al. [6] found that in subtropical forests, the community-weighted average of the maximum height of trees is the best predictor of multifunctionality. Functional diversity explains that the difference in EMF is significantly greater than species richness or microbial diversity. Similarly, Li et al. [3] found that functional diversity is the main driving factor in explaining the EMF of subtropical plantations. Even the community-weighted average leaf area provides a positive indirect effect through the enrichment storage of soil nitrogen and phosphorus. In terms of mechanisms, high FD enhances the complementarity of the neeth, in which coexisting species require different resources or functional roles to maintain multiple functions at the same time. Chen [1] synthesized these mechanisms, because tree FD can improve habitat productivity through complementarity and dominant effects, and then cagate at the nutritional level by increasing habitat heterogeneity and garbage yield. These nutritional feedbacks enable ecosystems with higher FDs to

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promote increasingly complex and resilient food web structures and stabilize versatility in a changing environment.

At the molecular level, a similar principle of functional diversity that promotes multifunctionality can be observed. Transcription factor SlGRAS9 acts as a regulator of genetic multifunctionality in the development of tomato fruit. Compared with the wild type, the SlGRAS9-CR line showed significant differences in gene expression. For example, as shown in Figure 1, among many functional categories, 1,997 genes were up-reguised and 3,092 were down-reguted. KEGG enrichment analysis shows that there is a significant correlation with secondary metabolism, plant hormone signals and photosynthesis pathways - similar to the way in which trait diversity provides multiple ecosystem functions. Further integration of RNA-seq and DAP-seq data identified 3,207 overlapping genes, indicating that SlGRAS9 directly regulates multiple transcription modules. Quantitative PCR confirms the coordinated regulation of representative downstream genes, which strengthens the concept of SlGRAS9 as a molecular multifunctional link (Figure 1).

Therefore, just as ecosystems rely on functional diversity to promote stability and performance, the SlGRAS9-mediated transcription network reflects how the regulated diversity of the gene level integrates functional metabolism, hormones or structural pathways. This parallelism of molecular and ecological FD shows that it may be crucial to maintain the site diversity of gene regulatory interactions to ensure the preservation of growth, adaptability and resility of environmentally variable plants [1].

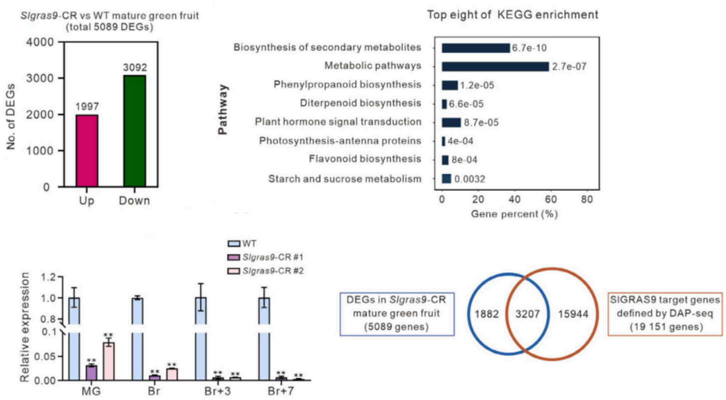

Figure 1. Pathways linking forest functional trait diversity to ecosystem multifunctionality (adapted from Chen et al. [1] , Fig. 3)

The image explains the way in which tree functional characteristics (such as leaf area index SLA, maximum tree height, root depth and wood density) determine multifunctionality (especially carbon fixation, nitrogen cycle and stability) through effects such as "resource complementarity effect - dominant effect - food web diffusion effect".

4. Phylogenetic diversity

Systemological diversity (PD) provides evolutionary depth for communities and can detect functional differences that may not be captured by feature data alone. Generally speaking, PD is usually associated with FD, but it can also have an independent influence. For example, a global dryland study shows that, in general, multifunctionality is strongly driven by the PD of subordinate plant species: the increase in the richness of early divergent bloodline (larger PD) and the increase in

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EMF in functional redundancy, and the characteristic influence of dominant species is less. This shows that protecting the phylogenetic line, not the protection of ordinary species, is important for preserving functions that may be considered functional redundancy. Similar to other studies, PD increases certain nutritional cycles or resilience, although there may be contextual differences. In forest areas, high PD is also accompanied by high FD, especially when diverse bloodlines have different characteristics (for example, conifers and angiosperms). Therefore, in general, PD seems to have a positive impact on multifunctional features, supplementing the impact of classification and functional diversity [7].

5. Structural diversity

Structural diversity is an ecological attribute related to the three-dimensional complexity of forest land, including tree crown stratification, tree size/diameter of breast height/height change, and spatial heterogeneity. It is increasingly recognised as a key driver of ecosystem multifunctionality (EMF) in forest ecosystems. In woodlands with heterogeneous structures, trees of different sizes can more effectively divide ground light and underground resources: large canopy trees will intercept sunlight, and smaller lower trees will use shadow micro-fields, which in turn will improve primary productivity and nutrient cycles [8]. Greater structural heterogeneity also promotes the vertical root partial layer, which can improve the efficiency of water and nutrient absorption, and is conducive to the buffering ability of the microclimate in the canopy [9].

As shown in Figure 2, the relationship between the topographic gradient (altitude = ELE; convexity = CON) and the bracket-level structural index and the structural diversity of the forest multifunctionality shows a positive correlation with the multifunctionality of the forest. As shown in the structural equation model of Wang et al. (Figure 2) [9], the terrain acts as an indirect driving factor of forest multifunctionality by affecting the structural components of diversity. Among all the predictors, the breast height and diameter change coefficient (DBH) (DBHCV) has the largest positive standardized path coefficient ($\beta = 0.14$ ***), which shows that size heterogeneity has made a meaningful contribution to multifunctionality compared with species richness and functional diversity. LaRue et al. [10] showed similar results in the continental-scale forest list, in which structural diversity is a better predictor of species diversity in ecosystem productivity. In woodland and savanna systems, Godlee et al. [8] found that changes in forest structure and tree density mediated the magnitude of the influence of biodiversity-functional relationships.

Mechanically speaking, forests with complex structures support high resource use complementarity, maintain stratified canopy habitats, and stabilize energy flow and nutrient circulation through spatial heterogeneity. However, excessive closure of the canopy or the dominant position of large trees will inhibit the growth of the lower layer, or both will cause functional trade-offs [9]. Management methods for enhancing electromagnetic fields and long-term resilience to climate change will include forest structures that emphasize structural heterogeneity, such as age unevenness, mixed species of forest land and selective sparseness. Therefore, compared with classification or functional diversity, structural diversity is often underrepresentative, which is an important and pragmatic goal to maintain the multifunctionality of forests.

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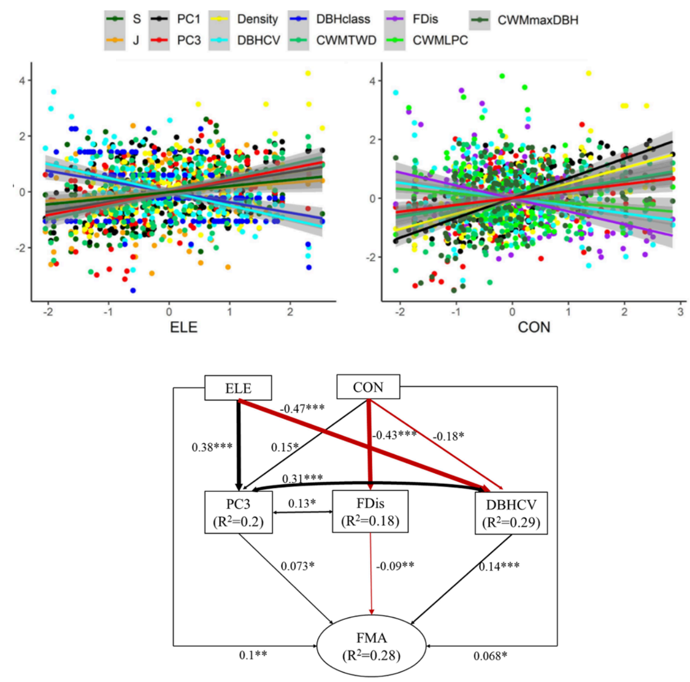

Figure 2. Conceptual and empirical relationships between structural diversity and ecosystem multifunctionality (adapted from Wang et al. [9] , Fig. 2–3)

The figure shows the vertical structure generated by the tree layer (tree-subtree-shrub-herbaceous plant) in the forest, and how DBH (breast height and diameter) changes to improve ecosystem productivity, nutrient cycle and carbon storage through light stratification, root complementarity or microenvironmental heterogeneity.

6. Belowground biodiversity and soil processes

Underground biodiversity, including soil microorganisms, such as bacteria, fungi and fauna such as nematodes and arthropods, are crucial to maintaining the versatility (EMF) of forest ecosystems. Soil bio-mediated decomposition process, nutrient mineralisation and carbon stabilisation. In the entire forest ecosystem, the diversity of soil microbial communities has been recognised as one of the strongest predictors of electromagnetic balance [11]. Diversified microbial communities enhance their ability to perform a variety of soil functions at the same time, such as nutrient retention, enzyme activity and greenhouse gas regulation, thus enhancing the overall resilience of the system.

The interdependence between surface and underground diversity is particularly important in forest ecosystems. Yuan et al. [12] found that the abundance of tree species and the diversity of soil microorganisms are important driving forces for the multifunctionality of temperate forests, among which the underground diversity mediates the above-ground biodiversity and nutrient cycle. Similarly, Lucas-Borja et al. [13] show that the richness of soil microorganisms and the complexity of nutrient networks are crucial to supporting synchronous functions such as carbon storage, nutrient transformation and soil respiration in Mediterranean forests. These prospects reveal that underground communities form an ecological interface that links the diversity of vegetation and soil processes.

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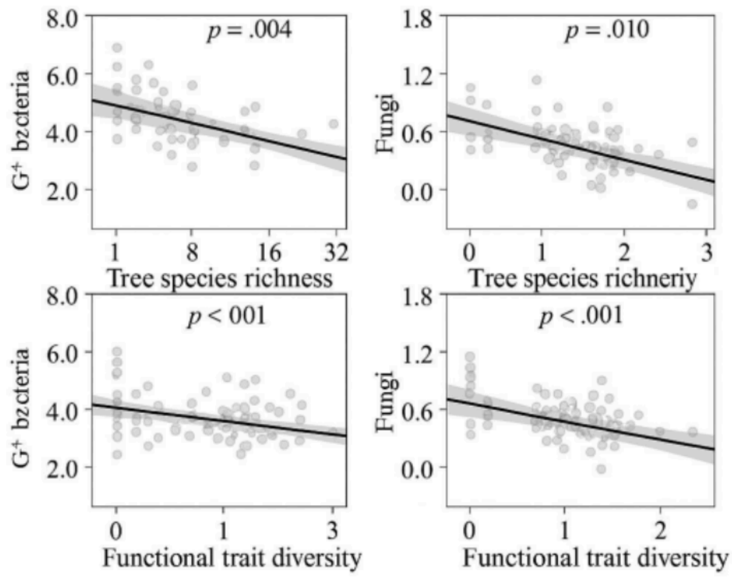

Figure 3. Structural equation model showing how tree species richness indirectly affects multifunctionality via soil microbial and nematode diversity (adapted from Shi et al. [2], Fig. 4)

Figure 3 shows that the abundance of tree species and functional diversity are negatively correlated with the abundance of Gram-positive bacteria and fungi, which shows that the composition of the microbial community is also changing with the increase of ground diversity. These changes in microbial composition may affect the dynamics of soil nutrients, thus changing the EMF of forest ecosystems. It is helpful to understand that the high underground biodiversity can maintain long-term ecosystem stability and multifunctionality by low-impact soil disturbance, maintaining coarse wood chips and root microbial symbiosis in tree planting.

7. Effects of anthropogenic disturbance

Human influences often change the diversity of forests, which will affect EMF. Homogeneous plantations and simplified forest structures (characteristics of intensive forestry) reduce the diversity and multifunctionality of habitats [4]. However, like the last bullet, a certain degree of interference can improve the resilience to pressure and functional transmission (wood and carbon). In addition to forestry, some low-level disturbances (low-intensity logging, trampling) can change soil and hydrology. Zhao et al. [5] provided evidence that human disturbances have led to significant changes in the soil moisture content of temperate forests in northeastern China; soil moisture loss is enough to deny the positive biodiversity functional relationship of middle and old forest land; the influence is reversed in young forest land, indicating that the impact is complex and depends on age. The author emphasizes the importance of protecting key non-biological (such as water) conditions; if disturbances change the basic drivers of the environment, even high biodiversity and/or multi-function transfer (rate) are unlikely to continue [5]. In summary, land use and forest management need to incorporate and protect multi-level diversity, as well as soil, water, etc., which support the evolving biodiversity to provide multiple functions.

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8. Synthesis: interactions among diversity dimensions

Different dimensions of diversity may interact with each other to promote multifunctionality. For example, species-rich forests are usually more complex in structure (i.e. vertical stratification that connects taxonomy and structure). The characteristics of dominant species will affect the structural complexity and functional results. Wang et al. [9] found that the dominant proportion of woody classification groups with large and low leaf P concentrations is high, which enhances multifunctionality and promotes structural changes. In addition to the dimension of diversity, the environmental background (for example, the influence of terrain or climate) can mediate these effects. For example, in Tiantong forest plots, altitude and slope indirectly affect EMF by filtering species communities and their consequent structural complexity [9]. From a management perspective, it is obvious that no single diversity indicator is sufficient; taxonomy, functional, phylogenetic and structural measures provide a more comprehensive understanding of EMF; for example, when developing recovery projects, not only species richness should be restored, but also a set of functional characteristics and support architecture should be restored to restore Multi-functionality [1].

9. Discussion

These findings confirm that the relationship with species richness and multifunctionality is usually the most understandable, but this relationship is complex. Most of the time, functional diversity and structural diversity in complexity tend to dominate the EMF relationship, and the importance of classification diversity may be related to the novelty of the feature combination of this diversity. It is important to understand that although the process of maintaining classification diversity enhances EMF, the relationship process is indirect, especially related to user knowledge. Phylogenetic diversity may capture this profound evolutionary feature mutation and enhance function [7]. Underground diversity may be the bottom-up driving force of the above-ground diversity effect through the relationship between nutrition and food network. Finally, they may be examples of external interference (or climate change) that affect the quality of species interaction [5]. Like all these factors affecting the transmission of biodiversity-multifunctionality, this has promoted conservation and forestry work, taking a more comprehensive view of the importance of species composition, functional characteristics and heterogeneous structures across nutritional levels and ecosystem contexts in maintaining electromagnetic warfare.

10. Conclusion

In summary, forest electromagnetic fields depend on the richness and organization of above-ground and underground biodiversity. A review of recent literature shows that maximizing changes in functional characteristics and structural heterogeneity is even more effective than simply enuming species [6]. Phylogenetic diversity, bloodline and microbial diversity all contribute to functional novelty, while the concurrency and complementarity of underground taxa maintain important ecosystem processes. Human behavior, such as the development of a single culture or artificial interference, and the use of invasive species, will either rapidly erode multifunctional results or may enhance them through diversified plantations [4]. So far, future forest restoration and management of these forests will be conducive to the inclusion of this work. For example, Chen et al. [1] proposed that forest management can design forests and restore ecosystem functions through designated feature combinations and sizes. In short, the multiple dimensions of protecting

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biodiversity (such as taxonomy, functionalis, phylogenetics and structure) are the key to maintaining the wide range of ecosystem services that forests now provide to us, and we may need these services under global changes.

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