The Relationship between the Functional Diversity of Plant Communities and the Functions of Ecosystems

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Abstract: This paper reviews the concept and research methods of plant community functional diversity, as well as the influence of functional traits on community assembly and ecosystem functions. Plant community functional diversity refers to the values and distribution range of functional traits of species within a community, which is an important aspect of biodiversity research. Studies have shown that functional diversity is an important predictor of ecosystem functions and is closely related to the resource utilization strategies, stability, disturbance resistance, and recovery capacity of communities. Although research on functional diversity has made certain progress, there are still challenges, including how to select appropriate functional traits, determine key resource limiting factors, and establish a standardized measurement system. Future research should focus on the response of functional diversity to environmental changes and its application in ecosystem management and biodiversity conservation.

Keywords: Functional Diversity; Ecosystem Function; Plant Community; Functional Traits

1. Introduction

As human civilization continues to evolve, numerous species and their natural habitats face increasingly severe degradation and disappearance. The resulting decline in biodiversity stems both from species' inherent biological characteristics and from external environmental changes [1]. The stability and integrity of ecosystem services are being significantly impacted by the decline in biodiversity. Therefore, thoroughly investigating and quantifying the underlying mechanisms linking biodiversity to ecological processes has become a critical issue requiring urgent attention in the field of ecological conservation [2]. When assessing the operational status of ecosystems, focusing solely on species richness is insufficient to fully reflect their functional characteristics. It is also necessary to incorporate systematic analysis of functional traits across various taxonomic groups. Functional traits, as the outward expression of species adapting to environmental fluctuations, manifest at the individual level as differences in plant morphology, physiology, and life history strategies [3,4]. Plants exert differential impacts on core ecosystem processes such as material transformation and energy transfer by adjusting their resource acquisition and allocation patterns to optimize their adaptability [5].

Functional diversity, as a core dimension within the biodiversity framework, focuses on the degree of variation in species traits within a community and their spatial distribution patterns. It reflects the differences and complementarities among species in their ecological functions [6,7]. This indicator not only reveals the dynamic changes in resource utilization efficiency but is also closely linked to ecosystem stability, disturbance resilience, and recovery potential. It serves as a key driver determining whether ecosystems can sustainably perform their functions [8,9]. Functional diversity integrates taxonomic information with functional trait data, making it an ideal tool for deciphering community assembly mechanisms and ecological processes in response to environmental change [10]. By leveraging a research framework centered on plant functional traits and functional diversity, we can uncover the ecological constraints and adaptive opportunities plants face under varying habitat conditions. This approach facilitates the prediction of community structure evolution trends and enables the assessment of functional diversity's contribution to ecosystem functional outputs [11,12]. Extensive empirical research has confirmed that factors such as community primary productivity, nutrient cycling rates, energy transfer efficiency, and resilience and recovery capacity against invasive species or environmental disturbances are all closely related to the level of functional diversity [13]. Since the 21st century, this field has gradually emerged as a hotspot in ecological research. By constructing multi-trait combination models, we can systematically analyze the driving mechanisms of multiple ecosystem functions, providing robust support for elucidating the complex interaction pathways between biodiversity and ecosystem functions [14,15]. In summary, systematically understanding the formation mechanisms and dynamic patterns of plant functional diversity not only deepens our comprehension of ecosystem functioning but also holds significant theoretical and practical value for addressing ecological risks arising from the sharp decline in biodiversity amid intensifying global climate change and frequent human disturbances [16].

2. Concept of Functional Diversity and Research Methods

2.1 Concept of Functional Diversity

Historically, domestic academic discourse on biodiversity decline has predominantly focused on quantitative indicators at the species level, such as species richness and composition structure. In contrast, functional diversity—the diversity of species functions—received limited attention in early research. However, as a core theoretical framework for elucidating community succession mechanisms, functional diversity has progressively integrated into biodiversity research over the past decade and has increasingly become a central focus within the field of ecology [17,18]. However, current field empirical studies remain scarce. Particularly in China, systematic empirical findings on the functional diversity of meadow plant communities are rarely reported, with existing research predominantly focusing on groups such as microorganisms, fish, birds, and benthic invertebrates [19,20].

To engage in in-depth discussion and scientific inquiry around a theoretical concept, it is essential to first precisely define its connotations, as this forms the foundation for subsequent research. In its early stages, functional diversity faced significant challenges in quantitative analysis due to the lack of a unified and clear conceptual definition, which also hindered the scientific assessment of its functional effects within ecosystems. Today, the ecological community widely adopts Tilman's 2001 definition: "the numerical characteristics of species functional traits within an ecosystem and their relative abundance." This is regarded as the most universally applicable conceptual framework to date [21]. Additionally, Díaz and Cabido defined functional diversity in 2001 as "the distribution of functional attributes, quantitative characteristics, and typological composition of species within an ecosystem [4]." Meanwhile, scholars such as Poos have proposed that functional diversity can be understood as the degree of differentiation in functional traits among different species within a community or ecosystem [22].

2.2 Research Methods for Functional Diversity

Research on functional diversity primarily focuses on: the selection of functional traits, the construction, comparison, validity analysis, and optimization of diversity measures; its effects on ecosystem processes and functions, along with underlying mechanisms; and the use of functional diversity to elucidate species coexistence and assembly patterns governed by functional differentiation. In 2005, Mason conducted an in-depth analysis and subdivided functional diversity into functional richness, functional evenness, and functional separation [23]. The introduction and refinement of numerous functional trait concepts have advanced methodological systems and opened new avenues for ecological research. Multiple indices are currently available for measuring functional diversity, with the most widely applied being: Functional Richness, Functional Evenness, and Functional Divergence. These respectively reflect a community's ecological space utilization, resource utilization, interspecific competition, and niche overlap. These indices provide valuable insights into community assembly processes and remain unaffected by species richness [24]. Although various measures of functional diversity have been proposed, such as Functional Attribute Diversity (FAD), Modified Functional Attribute Diversity (MFAD), one-dimensional functional evenness (FEs), Community Weighted Mean (CWM) for plant traits, and Functional Divergence Index (FDvar), existing measurement tools remain insufficient and limited in number. A standardized, efficient assessment system is urgently needed. Domestic research has predominantly focused on microorganisms and plants, with limited exploration of plant communities. (FDvar), existing measurement methods remain insufficient and limited in number. Standardized, efficient measurement systems urgently need to be established. Domestic research has primarily focused on microorganisms, while the plant domain remains in its exploratory phase. Although some achievements have been made, numerous challenges persist [25,26]. For instance, there is still no unified consensus on the identification and selection of functional characteristics, and research on functional diversity requires further investment and support.

In the field of ecology, biodiversity decline has consistently been a research priority, particularly regarding changes in species diversity and abundance structure. However, early studies often overlooked the critical dimension of functional diversity, which has gradually gained prominence over the past decade to become a research frontier. Functional diversity encompasses not only species diversity but also the roles and contributions of species within ecosystems, such as plant functional group dynamics, microbial functional variation, and food web complexity. Tilman's 2001 conceptual framework—which quantifies species functional traits and their relative contributions within ecosystems—provides a theoretical foundation, though its complexity poses practical challenges. Research has shifted from theoretical exploration to empirical assessments of its impacts on ecosystem processes. Refined metrics developed by Mason effectively reveal community assembly mechanisms while mitigating species richness confounding [27]. Existing measurement methods remain imperfect and require ongoing refinement. Overall, research on functional diversity continues to deepen, with its importance in ecosystem services and biodiversity conservation becoming increasingly prominent. Future work should focus more on identifying and selecting functional traits, as well as on how to efficiently integrate functional diversity theory into ecosystem management and conservation practices.

3. Relationship Between Functional Diversity and Functional Traits

The acquisition of functional diversity relies on the screening and quantification of functional traits. Precisely for this reason, it may offer distinct advantages in assessing a community's capacity to respond to environmental fluctuations and in predicting trends in ecosystem functional evolution. Simultaneously, as a key indicator of biodiversity, it also aids in revealing the logic underlying community assembly across different environmental gradients or spatial scales [28]. The analytical approach grounded in functional diversity aligns closely with the concept of ecological niches in community construction. According to niche theory, species possessing similar functional traits often perform analogous ecological functions and occupy comparable ecological niches [29]. As explained by Petchey et al, functional diversity can be understood as the multidimensional range of plant trait values covered within an ecosystem, that is, the degree of variation in plant functional traits. As emphasized by this concept, the fundamental purpose of functional ecology lies in transcending the limitations of taxonomic units to focus on the central role of organismal traits in explaining the mechanisms of their environmental responses and impacts [30]. The term “trait” was first introduced by Darwin. Functional traits broadly refer to various characteristics that directly influence an organism's performance. Through long-term adaptation, species gradually evolve morphological, behavioral, and physiological attributes that harmonize with their environment. These traits essentially constitute observable characteristics that determine an organism's adaptive capacity within specific environmental conditions [18, 31-33]. Such traits not only reflect a species' adaptive strategies to its environment and its interactions with abiotic and biotic factors, but also reveal the mechanisms of niche differentiation and coexistence [34]. At the same time, functional traits exhibit systematic changes in response to disturbance intensity, serving as early warning indicators of disturbance effects [31]. Investigations based on such traits facilitate a deeper understanding of species distribution patterns across environmental gradients and their response mechanisms to external changes. Beyond these advantages, functional trait analysis is not confined to specific species identities nor restricted by regional species pools. Consequently, its conclusions possess broader applicability than traditional taxonomic studies, making them readily transferable across different ecosystems [35]. For example, Lü Tingting found that the correlation between functional diversity and productivity is stronger than that between species diversity and productivity. Furthermore, a certain degree of flooding significantly influences the correlation between functional diversity and productivity. Zhang Lu's research indicates that appropriate grazing promotes species diversity, while mowing leads to declines in both species diversity and functional diversity. Functional traits—those morphological, behavioral, and physiological characteristics that directly influence an organism's performance—reveal a species' adaptive strategies and the ecological niche it occupies. These traits not only reflect the interactions between species and biotic/abiotic factors but also serve as early warning signals for ecosystem shifts when environmental disturbances occur. Despite progress in functional diversity research, several challenges remain. For instance, how to select appropriate functional traits to reduce prediction bias and enhance the broad applicability of research, and how to establish a standardized and efficient system for measuring functional diversity. Furthermore, research findings on functional diversity require more field-based empirical support to test their applicability and accuracy across various ecosystems. Future research should delve deeper into the relationship between functional traits and ecosystem processes, and explore how to integrate the concept of functional diversity into biodiversity conservation and ecosystem management practices.

4. Relationship Between Functional Diversity and Ecosystem Function

Ecosystem functions encompass processes, attributes, and stability. Regarding hypotheses on the effects of functional diversity, the diversity-quality ratio hypothesis and the diversity-productivity ratio hypothesis complement each other, revealing distinct relationships. Villéger point out that functional diversity in plant communities serves as an ecosystem driver and a key indicator for biodiversity assessment, characterizing the performance and function of organisms [36].

Research on the relationship between functional diversity and ecosystem functions has surged over the past decade, highlighting its significance in ecology. Essentially, the manifestation of functional diversity within ecosystems depends on heterogeneous resource utilization. The greater the variation in resource use, the higher the functional diversity, and consequently, the enhanced ecosystem functions [37]. As a component of biodiversity influencing ecosystem processes and functions, high functional diversity yields high productivity, resilience, and resistance to invasions [38]. However, its definition is broad and complex. In recent years, it has been defined as: the numerical values and ranges of functional traits across all species within a specific ecosystem, with the measurement representing functional trait diversity. Key functional traits of plants include specific leaf area, growth rate, plant height, leaf nitrogen and phosphorus content, seed dispersal and germination characteristics, relative abundance, seed mass, and phenology. Thus, functional diversity also refers to the variation in functional traits among species within a community. Functional richness indicates the extent to which species occupy functional space, determined by the range of functional trait values and functional niches within the community [39]. Díaz found that habitat heterogeneity led to increased variation in functional traits, improved resource use efficiency, elevated functional diversity indices, and enhanced ecosystem functions [4]. Beyond the species level, functional diversity at the intraspecific and genetic levels also influences ecosystem functions. Higher functional richness indices correlate with more efficient resource utilization and enhanced productivity [40]. Functional differentiation reflects the heterogeneity of functional trait values within a community. It not only indicates the probability of randomly selecting two species with identical functional traits but also reflects the degree of niche complementarity. A lower differentiation value signifies weaker complementarity and stronger competition [41]. Thus, communities exhibit high functional differentiation, enhanced nutrient use efficiency, and strengthened ecosystem functions. Functional evenness refers to the uniformity of species functional traits across ecological space, reflecting resource utilization efficiency. Functional diversity establishes connections between species and ecosystem functions through complementary resource use, and numerous critical ecological questions are closely related to it. While offering advantages over species diversity, functional diversity also has limitations [42]. Functional trait measurements are more objective than functional group classification, but trait selection still involves human factors. Especially when key factors with limited resources are involved, functional diversity can effectively predict community biomass production and function. However, identifying key limiting factors and related functional characteristics is challenging, and measurements are typically based on certain functional traits of species [43]. Due to the evolutionary conservation of functional traits in species, closely related species often share similar functional traits, making phylogenetic relationships a crucial factor.

5. Conclusion and Outlook

Functional diversity, as a core parameter quantifying variations in species functional attributes within communities, exhibits strong correlations with ecosystem functioning mechanisms. Compared to classical diversity measures, diversity indices constructed based on functional traits demonstrate superior predictive power for ecosystem functional performance, establishing themselves as the mainstream approach in biodiversity-ecological function (BEF) research. Despite the significant application potential of functional diversity analysis frameworks, practical implementation still faces challenges in selecting appropriate functional traits and identifying dominant resource-limiting factors. To enhance the precision of functional diversity assessments, future research should focus on refining measurement techniques to facilitate their effective application in ecosystem conservation and management practices. Concurrently, it is imperative to broaden the discovery dimensions of functional traits to comprehensively capture the roles organisms play within ecosystems; optimize functional diversity index systems to more scientifically and reasonably reflect the complexity of functional structures; and innovate statistical modeling and analytical strategies to explore the intrinsic relationships between functional traits and environmental factors.

Future research should also focus on areas that have not received sufficient attention, such as the interactions between above-ground and below-ground traits of plants and their combined effects on ecosystem functions, the mechanisms underlying ecosystem multifunctionality, the disturbance effects of global environmental change and consumer activity, and the coupling relationships between plant functional traits and ecosystem functions across scales. In-depth analysis of functional diversity requires integrating the theoretical foundations and technical methods of ecology, evolutionary biology, and environmental science to achieve multidisciplinary collaborative innovation. Overall, functional diversity—a richly nuanced and dynamically evolving multidimensional concept—will continue to occupy a central position in ecological research. Deepening our understanding of its underlying mechanisms will provide robust theoretical support for the sustainable management and conservation of fragile ecosystems like alpine meadows, and ultimately for global ecosystem health. Research priorities should also extend to investigating the response mechanisms of functional diversity to environmental disturbances, and exploring pathways to maintain and enhance ecosystem functional diversity through scientifically informed conservation and management strategies.

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