# Postprint: Advances in the Biogeography of Arbuscular Mycorrhizal Fungi

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## Abstract

Arbuscular mycorrhizal fungi (AMF) are ubiquitous in terrestrial ecosystems and can form mycorrhizal symbioses with the vast majority of higher plants. AMF can promote plant absorption of mineral nutrients, enhance plant stress resistance, and play important roles in maintaining ecosystem stability and productivity. AMF biogeography primarily investigates the biogeographic distribution patterns and community assembly mechanisms of AMF, which is crucial for understanding the importance of AMF in different ecosystems. This paper summarizes the latest research progress and methodologies in AMF biogeography and proposes a theoretical framework for AMF biogeography research. It is concluded that AMF are not simply randomly distributed in nature; host plants, geographic factors, climatic factors, and soil factors jointly determine AMF community structure, and AMF community assembly at different scales conforms to the niche-neutral continuum hypothesis, but the relative importance of these driving factors differs across scales. At global and regional scales, the geographic distribution patterns of AMF are mainly influenced by geographic distance and climatic factors, with neutral theory playing a greater role than niche theory. As spatial scale decreases, the influence of host plants and environmental factors on AMF communities surpasses the effects of geographic distance and dispersal limitation, and niche theory replaces neutral theory as the dominant force in AMF community assembly. Furthermore, many studies have found that the community assembly mechanisms of AMF in the same habitat are not static and can change with environmental variations. In future research, meta-analysis and data mining should be strengthened based on field surveys and public databases to further enrich and improve AMF biogeography theory.

# Full Text

## Preamble

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## Abstract

Arbuscular mycorrhizal fungi (AMF) are ubiquitous soil fungi in terrestrial ecosystems that form symbiotic associations with the majority of higher plants. Through mycorrhizal symbiosis, AMF facilitate plant uptake of mineral nutrients, enhance plant resistance to various environmental stresses, and play crucial roles in maintaining ecosystem stability and productivity. AMF biogeography focuses on the geographical distribution patterns and community assembly mechanisms of AMF, which is critical for understanding their ecological significance across different ecosystems. Here, we summarize recent advances in AMF biogeography, introduce the methodological approaches applied in this field, and outline a theoretical framework for future research.

Generally, AMF communities do not exhibit purely random distribution; instead, their community structure is jointly determined by host plants, geographical distance, climate factors, and soil physicochemical properties. Community assembly can be predicted by both niche theory and neutral theory at different spatial scales, supporting the niche-neutral continuum hypothesis. At global and regional scales, neutral theory plays a more important role than niche theory, with AMF distribution patterns primarily shaped by geographical distance and climate factors. However, at local and small scales, niche theory dominates. As spatial scale decreases, the influence of host plants and environmental factors on AMF communities surpasses that of geographical distance and dispersal limitation. The ecological processes driving AMF assembly change with environmental conditions, indicating that assembly mechanisms are not static but shift in response to environmental variation. Future research should strengthen integrated analysis and data mining based on systematic field surveys and public databases to further enrich and refine biogeographical theory.

**Keywords:** arbuscular mycorrhizal fungi; community assembly mechanism; scale; niche theory; neutral theory

## 1. AMF Geographic Distribution and Community Assembly Mechanisms

Community structure refers to the composition and quantitative characteristics of a community within a specific time period, typically described using parameters such as richness, dominance, and importance values. Community assembly refers to the mechanisms underlying the formation and maintenance of species diversity within a community and represents a core focus of biogeographical research. The primary hypotheses explaining community assembly mechanisms include niche theory, neutral theory, and the niche-neutral continuum hypothesis.

### 1.1 Neutral Theory

Hubbell proposed the unified neutral theory of biodiversity and biogeography, which posits that all species in an ecosystem are functionally equivalent and that species distributions are widespread and random, primarily influenced by geographical distance and dispersal limitation. Many studies have shown that AMF are widely distributed across global habitats, suggesting that neutral stochastic processes play crucial roles in community assembly. When studied habitats encompass large spatial scales and environmental gradients, neutral theory becomes particularly important in shaping community composition and geographical distribution patterns. Van der Gast et al. found that dispersal limitation largely determines the relative abundance of species in AMF communities, and that -diversity decreases with increasing geographical distance, following the classic distance-decay pattern in biogeography. These findings confirm that at global scales, neutral theory dominates in explaining AMF distribution and community assembly.

### 1.2 Niche Theory

Grinnell originally defined the niche as the unit of limiting environmental factors occupied by a species, representing both a spatial unit of the environment and a species' position within it. Niche theory is based on deterministic processes, where environmental filtering and competitive exclusion dominate community composition. Numerous studies have demonstrated that environmental factors and host plants significantly influence AMF diversity and community structure. For example, Kohout et al. found that temperate grassland AMF communities were affected by spatial distance between sampling sites, but soil environmental factors and host plant growth stage played more important roles. Fitzsimons et al. showed that soil physicochemical factors and nitrate-nitrogen content could effectively predict AMF community structure. These studies collectively indicate that niche theory occupies an important position in AMF community assembly.

### 1.3 Niche-Neutral Continuum Hypothesis

Although niche theory and neutral theory are distinct, both have successfully explained AMF community assembly and diversity patterns. Gravel et al. integrated these theories into the niche-neutral continuum hypothesis, proposing that community assembly involves both neutral processes and niche influences, with their relative importance forming a continuous spectrum from neutral to niche poles. Increasing evidence shows that the relative importance of these processes varies across ecosystems and spatial scales. Some studies suggest that AMF community structure results from the combined effects of dispersal limitation, environmental filtering, and species interactions. Others argue that the relative importance of niche and neutral theories in determining AMF community structure may shift with environmental changes. For instance, Hazard et al. found that in alpine meadow ecosystems, as toxic plant spread intensified, AMF community composition shifted from phylogenetically random to phylogenetically clustered, indicating that environmental filtering became the dominant factor in the presence of toxic plants. These results demonstrate that AMF community assembly cannot be explained by a single theory but likely involves both stochastic genetic drift and niche differentiation.

## 2. Scale-Dependent Patterns in AMF Geographic Distribution and Community Assembly

Scale is a fundamental concept in natural and social sciences, representing the spatial or temporal dimension of a research object. As a key paradigm in ecology, scale serves as a bridge linking pattern and process. The relative contributions of geographical distance and environmental factors to microbial distribution patterns are scale-dependent.

### 2.1 Global Scale

Global-scale biogeographical studies compare community distribution patterns across different continents, climate zones, and ecosystems. Research indicates that at the global scale, AMF distribution shows low heterogeneity, likely due to effective dispersal through abiotic and biotic pathways. However, community structures in different habitats are closely related to environmental factors and spatial distance. AMF taxa are phylogenetically clustered, and -diversity decreases with geographical distance, following the distance-decay pattern. These findings confirm that neutral theory dominates in explaining AMF distribution and community assembly at global scales.

## 2.2 Regional Scale

Regional-scale studies typically cover large geographic areas with substantial variation in vegetation and other factors, often encompassing countries or extensive regions. At this scale, AMF distribution patterns are influenced by geographical distance and dispersal limitation, but also correlate strongly with soil physicochemical properties. Studies in northern China and Switzerland have shown that geographical factors such as latitude and soil conditions are more important than land management practices in determining AMF communities. Environmental heterogeneity emerges as a primary driver of regional-scale distribution patterns. These results indicate that neutral theory remains important, but environmental factors play increasingly significant roles in community structure.

## 2.3 Local Scale

Local-scale research focuses on smaller areas with relatively uniform climate but variable soil and vegetation factors. At this scale, soil factors and host plants become the dominant determinants of AMF community structure. Studies have shown that soil available phosphorus strongly influences AMF communities, and that vegetation type and soil factors are the most important environmental variables. Host plant changes can also alter soil AMF composition, with plant invasions increasing AMF richness and abundance. Overall, at local scales, community structure is closely related to soil physicochemical properties and host plants, with niche theory playing the dominant role in community assembly.

## 2.4 Small Scale

Small-scale studies are conducted in fixed plots with consistent climate and minimal dispersal limitation. In these settings, AMF communities often show spatial autocorrelation and respond sensitively to environmental changes. Research has demonstrated that waterlogging increases AMF species richness, fertilization significantly alters community composition, and adding nitrogen-fixing legumes enhances AMF communities. These findings indicate that ecological niche theory plays a crucial role in shaping AMF communities at small scales, and that community assembly mechanisms can shift in response to environmental changes.

## 2.5 Altitude and Temporal Scales

Research on AMF community patterns along altitude and temporal gradients remains limited. Studies show that AMF community structure varies with altitude, often peaking at mid-elevations, though some report decreasing diversity with increasing altitude. These differences likely result from variation in soil properties and host plant communities across elevations. Temporally, AMF communities exhibit seasonal and interannual variations, with seasonal changes related to climatic factors and interannual variations associated with ecosystem succession. These results suggest that AMF communities show clear niche differentiation along both altitudinal and temporal gradients.

## 3. Summary

AMF are not randomly distributed in nature but show non-random patterns influenced by environmental factors and host plants. The primary drivers of geographic distribution and community assembly mechanisms vary across scales. Our synthesis of recent research suggests a theoretical framework where AMF community structure is shaped by both niche and neutral theories across all scales, consistent with the niche-neutral continuum hypothesis. However, the relative importance of these theories changes with scale: at global and regional scales, neutral theory dominates as geographical distance and climate factors primarily shape distribution patterns; as spatial scale decreases, host plants and environmental factors become more important than dispersal limitation, and niche theory replaces neutral theory as the dominant assembly mechanism. Importantly, these assembly mechanisms are not static but shift with environmental changes.

[Figure 1: see original paper] Theoretical framework for studies on biogeography of arbuscular mycorrhizal fungi

## 4. Outlook

The emergence of molecular biology, particularly high-throughput sequencing, has greatly facilitated AMF biogeography research. Future studies should combine large-scale field surveys, multi-factor experiments, and data mining of public databases to systematically investigate key factors and regulatory pathways affecting AMF community structure across different habitats. Integrating data across scales and ecosystems will provide convenient means to explore AMF biogeographical patterns and underlying mechanisms. Drawing on traditional biogeographical models such as island biogeography theory will help develop comprehensive models for AMF distribution and assembly mechanisms.

Current research has focused primarily on spatial scales, with limited reports on temporal and altitudinal gradients. Future work should examine AMF community changes during vegetation succession at small scales and preserve soil samples from the same sites across different periods for temporal dynamic studies. Combining spatial and temporal scales will provide a more comprehensive understanding of AMF community dynamics, enabling better predictions of how future environmental changes will affect ecosystem structure and function and informing environmental change mitigation strategies.

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