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Scale Effects on Species Abundance Distribution Patterns of Desert Plants in the Ebinur Lake Region: Postprint

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Abstract

This study examined the desert ecosystem of the Ebinur Lake Basin, selecting a 1 hm^2 sample plot of desert plant community. Based on six sampling scales (5 m × 5 m, 10 m × 10 m, 20 m × 20 m, 25 m × 25 m, 50 m × 50 m, 100 m × 100 m), different ecological models were employed to fit the distribution patterns of plant communities, thereby determining the dominant ecological processes driving community assembly in desert ecosystems and the influence of scale effects on community assembly. The results showed that: (1) With increasing spatial scale, the proportion of rare species in the community gradually decreased, while that of common species gradually increased; (2) Species rank-abundance curves revealed that species richness increased with scale and species distribution became more uniform; (3) Model fitting results indicated that the species abundance distribution of desert plants was consistent with predictions from neutral models and statistical models, whereas niche models failed to pass the test ($P < 0.05$); (4) With increasing scale, the species richness index and Shannon-Wiener index increased accordingly, while the Simpson index and Pielou index exhibited opposite trends. In summary, although desert ecosystems exhibited significant changes in community composition across different scales, the ecological processes influencing species abundance distribution patterns were fundamentally consistent, and neutral theory could be preliminarily inferred to be more important in maintaining species diversity in desert plant communities.

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Full Text

Scale Effects on Species Abundance Distribution Patterns of Desert Plants in the Ebinur Lake Basin

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Abstract

This study investigated the desert ecosystem of the Ebinur Lake Basin, establishing a 1 hm^2 desert plant community sample plot. Based on six sampling scales (5 m × 5 m, 10 m × 10 m, 20 m × 20 m, 25 m × 25 m, 50 m × 50 m, and 100 m × 100 m), we employed various ecological models to fit the species abundance distribution patterns of plant communities, thereby identifying the dominant ecological processes governing community assembly in desert ecosystems and assessing the influence of scale effects. The results demonstrated that: (1) As spatial scale increased, rare species gradually decreased while the proportion of common species increased. (2) Species rank abundance curves revealed that species richness increased and species distribution became more uniform with expanding scale. (3) Model fitting results indicated that desert plant species abundance distributions were consistent with predictions from neutral models and statistical models, whereas niche models failed all tests ($P < 0.05$). (4) With increasing scale, the species richness index and Shannon-Wiener index increased, while the Simpson index and Pielou index exhibited opposite trends. In summary, although community composition in desert ecosystems showed clear scale-dependent variation, the ecological processes influencing species abundance distribution patterns remained fundamentally consistent across scales. These findings suggest that neutral theory plays a particularly important role in maintaining species diversity within desert plant communities.

Keywords: desert plant community; species abundance distribution; ecological process; scale effect; neutral process; Ebinur Lake Basin

Introduction

The mechanisms underlying the formation and maintenance of biodiversity—community assembly mechanisms—have long been central topics in ecology.

Species abundance distribution (SAD), which describes the number of individuals for all species in a community from common to rare, represents a fundamental aspect of community structure and effectively reflects the basic processes of community assembly. Since the 1940s, SAD has served as a starting point for population and community ecology research and remains a core issue in ecological science. Studying plant abundance distribution patterns enhances our understanding of species composition and distribution regularities within communities, providing theoretical foundations for community assembly, biodiversity, and biogeography.

In recent years, research on SAD patterns has seen continuous methodological advances, including the application of many new models. Different fitting models represent different ecological processes, with diverse types being widely applied. Current models fall into three categories: purely statistical models, neutral theory models, and niche models. Studies have found that different plant communities are best described by different models. For example, desert plant communities under high water-salt stress conform to the lognormal model within statistical models, while comparisons of evergreen and deciduous tree distribution patterns show optimal fit with neutral theory models. Research on grassland species abundance distribution under different utilization patterns identifies the broken stick model within niche models as most appropriate. Because ecological processes exhibit scale dependency, single-scale studies may be insufficient to address relevant scientific questions, making multi-scale investigations of SAD patterns a recent research focus. However, most studies examining SAD patterns have concentrated on species-rich ecosystems such as forests and grasslands, with limited in-depth research in arid desert regions.

Arid and semi-arid regions constitute important components of global terrestrial ecosystems. Characterized by scarce precipitation and water resources, these areas are highly sensitive to global climate change and represent critical regions for biodiversity research. The Ebinur Lake Basin in Xinjiang is a typical temperate arid desert zone. This study selected desert ecosystems in the Ebinur Lake Basin as the research object, employing seven commonly accepted and widely used abundance models to fit actual surveyed communities across different scales. Through comparative analysis, we examined whether species abundance patterns across different scales are influenced by random neutral processes or non-random niche processes, providing scientific evidence for understanding abundance patterns in typical desert plant communities and theoretical references for community assembly in arid regions.

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1. Study Area Overview

The Ebinur Lake Wetland National Nature Reserve (45°09 N–44°31 N, 82°33 E–83°53 E) is located in China' s northwestern border region, situated along the main channel of Atlantic westerly airflow at Alashankou. The Ebinur Lake

Basin has an average elevation of 189 m, with an annual average precipitation exceeding 100 mm that is unevenly distributed across seasons (more in summer, less in winter). The climate belongs to the mid-temperate continental arid type, with an extreme minimum temperature of -36°C, extreme maximum temperature of 44.6°C, and annual average evaporation of approximately 1600 mm. The reserve integrates desert and wetland landscapes, featuring rich geomorphological features and biodiversity resources. Soil types include zonal soils such as gray desert soil, gray-brown desert soil, and aeolian sandy soil, as well as intrazonal soils including solonchak, meadow soil, and swamp soil. Dominant plant species include *Haloxylon ammodendron*, *Populus euphratica*, *Phragmites australis*, *Nitraria tangutorum*, *Glycyrrhiza uralensis*, *Lycium ruthenicum*, *Aeluropus pungens*, *Halostachys caspica*, *Halocnemum strobilaceum*, *Tamarix chinensis*, *Suaeda pterantha*, *Kalidium foliatum*, *Reaumuria soongorica*, and *Halimodendron halodendron*.

2. Methods

2.1 Sample Plot Establishment and Survey Within the Ebinur Lake Wetland Nature Reserve, we established a 100 m × 100 m vegetation community sample plot perpendicular to the desert riparian forest north of the Aqikesu River near the East Bridge Management Station [Figure 50: see original paper]. The large plot was divided into 5 m × 5 m continuous quadrat units. Community surveys were conducted in all quadrat units, recording species names and abundances for arboreal and shrub plants. Herbaceous plants were surveyed within 1 m × 1 m sub-quadrats within the 5 m × 5 m units, recording species names, individual counts, height, and coverage.

2.2 Species Abundance Representation Species abundance data were derived from individual counts recorded during community surveys. To intuitively and clearly observe species abundance distribution within communities, we employed histogram methods and rank abundance distribution (RAD) curves. For histogram representation, species individual counts were grouped into abundance intervals (1–4, 4–16, 16–64, etc.) before grouping. In rank abundance curves, the x-axis represents species rank (all species sorted from highest to lowest abundance), while the y-axis represents the corresponding individual counts for each rank.

2.3 Model Selection We selected seven widely accepted abundance models to study species abundance patterns: two purely statistical models (lognormal model, logseries model), two neutral theory models (metacommunity zero-sum multinomial model, Volkov model), and three niche models (niche preemption model, broken stick model). Each model is briefly described below.

2.3.1 Purely Statistical Models (1) Lognormal Model

Proposed by Preston in 1948 and applied to ecological SAD research, this model assumes that the logarithm of species individual counts follows a lognormal distribution. If the abundance of the ith species is denoted as $A = e\widehat{(} + \log(2) \times \delta)$, the formula is:

$$S(A) = \frac{S_0}{\sqrt{2\pi}\delta} \exp\left[-\frac{(\log_2 A - \mu)^2}{2\delta^2}\right]$$

where represents the mean of the normal distribution and δ is the variance.

(2) Logseries Model

Proposed by Fisher et al. in 1943, this model mathematically describes the relationship between species number and individual count, excluding species with zero individuals. Considered among the best-performing theoretical distribution models, its formula is:

$$S(n) = \frac{\alpha X^n}{n}$$

where n is abundance, S is species number, and α and X are constants (α serves as a diversity index similar to species richness). Typically, X satisfies $\Sigma(\alpha X^n/n) = S$ and is related to community size.

2.3.2 Neutral Theory Models (1) Metacommunity Zero-Sum Multinomial Model

This model posits that species abundance distributions at any site result from random drift processes in the metacommunity. Containing parameters for site species individuals (J) and fundamental biodiversity number ( ), the model calculates the number of species S with abundance n in a local community sample through:

$$S(n) = \theta \frac{J!}{n!(J-n)!} \frac{\Gamma(\gamma)}{\Gamma(J+\gamma)} \int_0^\infty \frac{e^{-y} y^{n-1}}{(1+y/\gamma)^{J-n}} dy$$

where represents the fundamental diversity index, J is total community abundance, y is a species' abundance, and Γ denotes the Gamma distribution representing the distribution of abundance n required for S species occurrence.

(2) Volkov Model

Built upon the metacommunity zero-sum multinomial model, the Volkov model adds a migration coefficient m, assuming constant migration rates from metacommunity to local community:

$$S(n) = \theta \frac{J!}{n!(J-n)!} \frac{\Gamma(\gamma)}{\Gamma(J+\gamma)} \frac{\Gamma(n+\gamma m)}{\Gamma(\gamma m)} \frac{\Gamma(J-n+\gamma(1-m))}{\Gamma(\gamma(1-m))}$$

where n is species abundance, m is migration rate, is the fundamental diversity index, J is total community abundance, and γ represents the number of individuals migrating to the local community.

2.3.3 Niche Models (1) Niche Preemption Model
Also called the geometric series model, this assumes the first species occupies proportion k of the total niche, the second species occupies proportion k of the remaining niche (i.e., k(1-k)), continuing until remaining resources are insufficient to support another species:

$$A_i = A_1(1-k)^{i-1}$$

where A represents the abundance of the ith species and A_1 is the predicted abundance of the most dominant species.

(2) Broken Stick Model
A resource allocation model treating total resources as a unit-length stick randomly divided at S points into S segments utilized by S species. Assuming species are taxonomically and competitively similar and appear simultaneously in the community, the abundance of the ith species A is:

$$A_i = \frac{J}{S}\sum_{x=i}^{S}\frac{1}{x}$$

where i is the ith surveyed species and S is the total number of surveyed species.

2.4 Model Testing We employed the Kolmogorov-Smirnov (K-S) test based on cumulative distribution functions to compare frequency distributions with theoretical distributions, testing for significant differences through 1000 bootstrap resamplings. Models were considered acceptable when $P > 0.05$. Additionally, we used the widely applied Akaike Information Criterion (AIC) for model comparison, where smaller AIC values indicate better fit.

2.5 Data Processing Data preprocessing was completed in Excel 2013. Species abundance distribution graphs, rank abundance curves, and model fitting were performed using R packages. Species diversity indices were calculated using the vegan package, with formulas as follows:

- **Species Richness Index**: S = total number of species
- **Shannon-Wiener Diversity Index**: H' = -$\Sigma P \ln P$
- **Pielou Evenness Index**: $E = H' / \ln S$
- **Simpson Dominance Index**: D = 1 - ΣP^2

where S is species number and P is the proportion of abundance contributed by the ith species.

3. Results

3.1 Species Abundance Distribution Patterns Across Scales Species abundance histograms [Figure 2: see original paper] revealed that rare species (those with 1-4 individuals) constituted a large proportion of the entire community, with rare species numbers decreasing as scale increased. Conversely, common species proportions gradually increased across scales. At small scales, species abundance distributions showed that single-individual species were most numerous, while common species numbers increased with spatial scale expansion.

Rank abundance curves at different scales [Figure 3: see original paper] exhibited consistent trends, though species richness varied at each scale. At small scales (5 m × 5 m, 10 m × 10 m), curves spanned narrow ranges on the x-axis, indicating low species richness. As scale increased, curve spans gradually widened, with greater richness at larger scales (25 m × 25 m, 50 m × 50 m, 100 m × 100 m). Curve flatness reflected species distribution evenness—curves became progressively flatter with increasing scale, indicating more uniform species distribution.

3.2 Model Fitting of Species Abundance Distribution Patterns We fitted seven models to communities at different scales and analyzed their performance. K-S test results showed that neutral theory models and statistical models were accepted at all scales, while both niche models (niche preemption and broken stick) failed all tests ($P < 0.05$) . AIC values indicated the first five models showed good fit across all scales, with better performance at smaller scales.

At small scales (5 m × 5 m, 10 m × 10 m), the logseries model showed the smallest AIC values (5 m × 5 m: 43.15; 10 m × 10 m: 56.73), indicating optimal fit. At medium scales (20 m × 20 m, 25 m × 25 m), model fitting performance ranked as: logseries model > metacommunity zero-sum multinomial model > Volkov model > lognormal model > broken stick model, with niche models rejected. At larger scales (50 m × 50 m, 100 m × 100 m), neutral theory and statistical models both performed well with minimal AIC differences (maximum 2.88). Combined with fitting results [Figure 4: see original paper], statistical and neutral models showed closer alignment with actual surveyed community SADs.

Total community abundance increased with scale . Species abundance composition at small scales featured numerous rare species, while common species gradually increased at larger scales. Most species maintained low abundance, with only a few being common across scales. Neutral theory predictive parameters showed that fundamental diversity index ( ) and species migration rate (m) decreased with increasing scale. Among diversity indices, species richness and

Shannon-Wiener index increased with scale, while Simpson and Pielou indices showed opposite trends.

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4. Discussion

Species diversity patterns vary with scale, and the role of ecological processes differs across scales. Our model fitting results showed that the same models yielded consistent test results across all sampling scales, with neutral theory and statistical models performing well and showing similar goodness-of-fit rankings, while niche models failed all tests. This indicates that although community composition (proportions of rare vs. common species) differed across scales, species abundance distribution patterns showed no significant distinction, suggesting that the ecological processes governing species distribution may be similar across sampling scales.

Species abundance histograms intuitively describe community abundance changes, revealing differences among rare, intermediate, and common species and facilitating interpretation of community species composition. In this study, Ebinur Lake Basin plant communities showed clear scale-dependent trends in species abundance. Each species' abundance increased with scale, leading to increased total abundance across scales. For small scales, single-individual species were most numerous, while common species increased with spatial expansion.

Species abundance patterns are typically described and analyzed through fitted curves, with different models representing different ecological processes and mechanisms. Comprehensive application of multiple models can better interpret the ecological significance of different plant communities. Previous studies on subtropical secondary forests also found that statistical and neutral models performed well at every scale, while niche model fit significantly weakened and was rejected. Our results align with these findings.

Statistical models describe relationships between species abundance patterns and quantities, whereas neutral models more easily explain mechanisms maintaining community abundance distributions. Therefore, neutral processes may exert greater influence on this plant community' s structure, potentially representing the primary mechanism maintaining SAD. Related research indicates that neutral processes dominate species abundance distribution in regions with significant environmental variation. The scale variation in our study may also constitute a form of environmental variation, and our finding that neutral processes dominated SAD patterns across scales aligns with these results.

Species diversity indices measure species quantity and evenness within communities. Many studies reveal that neutral theory becomes increasingly important as diversity indices increase. In this study, as sampling scale expanded, species richness and Shannon-Wiener indices increased, while migration rates showed

declining trends (though unchanged at small scales), indicating that neutral processes play important roles at larger scales and explaining why neutral theory models showed optimal fit. Increased diversity indices also resulted from limited sample sizes at small scales—expanding sampling area increased sample size and spatial heterogeneity, thereby enhancing community diversity.

Neutral and niche processes are not mutually exclusive, and community SAD is not entirely based on either theory alone. Many studies suggest that pattern and process may not correspond one-to-one in ecology. While SAD analysis helps understand biodiversity maintenance mechanisms, inferring ecological roles from pattern analysis may have limitations. Our results show Ebinur Lake Basin desert plant SAD patterns align with neutral model predictions, but this does not necessarily indicate equal competitive ability among species or that community assembly is dominated by random processes. We can speculate that when niche process influence is low in determining community composition, neutral process influence may increase. From a diversity perspective, if plant populations are randomly or regularly distributed in space, spatial variation in species diversity would not change with scale.

This study utilized species abundance curves across different sampling scales to analyze desert plant community distribution patterns and explore assembly mechanisms. However, abundance curve fitting only uses quadrat abundance data containing limited community information. To more precisely study actual community abundance patterns, future research should incorporate environmental factors (topography, soil), biological factors, and other spatial factors.

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5. Conclusions

1. Ebinur Lake Basin desert plant communities exhibited clear scale dependence in community structure. Rare species dominated at small scales, decreasing in number with scale expansion while common species gradually increased. Most species maintained low abundance, with only a few being common.

2. Model fitting results showed that neutral and statistical models performed similarly across all six scales, while niche models failed all tests. This indicates that species abundance distribution patterns in Ebinur Lake Basin desert plant communities may share similar maintenance mechanisms across scales.

3. Neutral models showed the best fit, suggesting that stochastic processes may play important roles in desert plant community assembly. We can preliminarily infer that neutral theory is particularly important for maintaining species diversity in this community.

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