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Patterns of family-species distribution for organisms in Alabama, USA

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ABSTRACT Biodiversity provides multiple functions to human society. Understanding the emergent properties of biodiversity in one region is important for better conservation and strategy developing. In this study, organisms of different groups (fishes, amphibians and reptiles, mammals, butterflies and plants) in Alabama were studied by methods of family-species number distribution and entropy. The results indicate that the family-species distribution of each organism group in Alabama follows a power law, but the power exponent varies among groups. There is no significant difference for the power exponents among the groups of fishes, mammals and plants, also between amphibians and reptiles and birds. The power exponent of butterflies is quite different with others. For global birds, the power exponent is significantly different with the birds group and others in Alabama. The entropy of family-species distribution is only about half of maximum entropy within each group or overall. The implications for biodiversity conservation and strategy making are discussed. Characterizing the family-species distribution at different scales will provide a quantitative approach for comparing and evaluating hierarchical properties of biodiversity.

KEY WORDS Biodiversity; emergent property; entropy; evolution; power laws.

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INTRODUCTION

Human societies are connected to and dependent on the biodiversity and its functions through the flow of materials and energy (e.g., Costanza et al., 1997; Daily, 1997). The last several decades have been marked by important discoveries and scientific advances in our understanding of biodiversity. One of the fundamental questions in ecology is why there are various species coexisting in nature (e.g., Hutchinson, 1959; May, 1972). Understanding the macroscopic patterns of species diversity may provide better strategies for biodiversity conservation at a large scale from a holistic perspective. When biodiversity is referred in the context of species abundance and above, there is a general pattern emerged: a few taxonomic groups have more species number but most have limited species number. Yule (1925) studied taxonomic abundance distribution in genera and proposed a continuous branching process model to explain the distributions at the generic level and found that they were power laws in the limit of equilibrated populations. This frequency distribution of species within taxonomic groups has the shape known as “hollow curve” (Willis & Yule, 1922). Burlando (1990; 1993) tested the fractal geometry hypothesis through the examination of size-frequency distributions of taxa with different numbers of subtaxa. Late more and more studies indicated the geometric nature in biota and its possible relationship with speciation and extinction in evolutionary processes (e.g., Chu & Adami 1999; Scotland & Sanderson 2004; Maruvka et al., 2013). This leads to the important hypotheses that fractal nature or power laws can describe the scaling relationships in the emergent patterns of biodiversity at different scales although the underlying processes may be complicated (e.g., Brown et al. 2002; Marquet et al., 2007; Lorimer et al., 2015). Furthermore, all the species of different families in this region are formed as a self-organized network, such as regional biota. The species network should follow the principle of maximum entropy (MaxEnt),which means the probability distribution of species best represents the current state and reaches the largest entropy(e.g., Jaynes, 1957). MaxEnt has been frequently used in ecology (Harte, 2011). It can be assumed that species within families follow MaxEnt during their evolution and development. But more case studies from the different parts of world are needed to show the validity of scaling relationships and possible implications.

The state of Alabama is located in the southern region of USA, which is well known for its high biodiversity due to its warm climate and natural geography (Mount, 1975). The terrestrial habitats span from the gulf beaches to the lower Appalachian Mountains. The state also contains a wealth of water and wetland resources. The Mobile-Tensaw Delta is recognized as one of the most significant and important delta complexes in the nation. The great physical diversity provides habitat for abundant wildlife and plant species. Alabama is consistently ranked among the top three to five states in terms of overall biodiversity based on the report from Alabama Department of Conservation and Natural Resources (www.outdooralabama.com). However, due to increasing human population, urbanization and agricultural development (Chen, 2010), the biodiversity conservation in Alabama is under challenge. Huge effort was spent to document species in Alabama (e.g., Mount, 1975; Mettee et al., 1996; Mirarchi, 2004). It is necessary to study overall species at state level as a whole because some properties of complexity can only emerge at a large scale (Noss & Harris, 1986; Green et al., 2006; Chen, 2008). The goal of this study is to find the patterns of family-species number distribution for organisms in Alabama. The specific objectives include (i) whether the patterns of family-species number distribution follow power laws; (ii) whether similar power laws exist in family-species number distribution for different organism groups (e.g., fishes, birds, mammals and plants); (iii) whether species from different families follow or close to MaxEnt within each group or overall; and (iv) whether there are possible implications for biodiversity conservation.

MATERIAL AND METHODS

Study area

Alabama is located in the southern region of USA, which is between the southern foothills of the Appalachian Mountain Range and the Gulf of Mexico (between 31° and 35°N). Alabama has a warm, humid, subtropical climate. Summers are hot and humid with an average high temperature around 33°C. The driest times of the year are usually in late summer and fall. Winters are cold and wet. Regional annual precipitation varies from 150 to 162 cm in the north part and 180 to 195 cm along the coast (Carter & Carter, 1984). Forests cover roughly two-thirds of the state and reach about 8.9 million hectares (Chen, 2010). Alabama is ranked as the third largest commercial forest industry in the nation after Oregon and Georgia. But Alabama's forests are far more diverse than those of Oregon and Georgia with a comparable abundance of forested acreage (Phillips, 2006). Tree species in Alabama was documented to vary from 145 to 193 while compared to an estimated 16 to 60 species occurring in Oregon (Ricketts et al., 1999). Due to the combination of mild and humid climate, remarkable surface drainage and diverse physiographic subdivisions, the species of Alabama have reached a high level diversity (Mount, 1975; Mettee et al., 1996). It is therefore an important consideration for research and conservation in the USA.

Dataset

The dataset includes the information of species in each family for fishes, amphibians and reptiles, birds, mammals, butterflies and plants. The detailed information is listed in Table 1.

The data of global birds were also used for comparison.

Data sorting and statistics

For each organism group, the family numbers and species number within each family were counted and recorded. Then, family numbers (p_i) with species number $x_i < 5, 10, 15, \ldots, N$ were counted respectively. N is the maximum number of species in a family. After then, the accumulated percentage (y_i) of family number in total families was calculated as:

$$y_i = \frac{p_i}{p_{N+1}} \times 100$$

where p_i is the family number with species number less than i, and p_{N+1} is the family number with species number less than $N+1$, which is also the total family number.

	Family number	Species number	Data sources	Power laws	R^2 and p
Fishes	40	336	Mettee et al., 1996	$y=0.0873x+1.8337$	$R^2=0.8313$ $p<0.05$
Amphibians and reptiles	28	183	Mount, 1975	$y=0.1451x+1.7546$	$R^2=0.9262$ $p<0.05$
Mammals	24	77	Mirarchi, 2004	$y=0.0985x+1.8673$	$R^2=0.9683$ $p<0.05$
Birds	60	324	Mirarchi, 2004	$y=0.156x+1.759$	$R^2=0.9329$ $p<0.05$
Butterflies	6	139	Howell & Charny, 2010	$y=0.6485x+0.8542$	$R^2=0.9513$ $p<0.05$
Plants	240	4273	Alabama Herbarium Consortium (http://floraofalabama.org)	$y=0.0803x+1.8017$	$R^2=0.6036$ $p<0.05$
Global birds	145	9698	Monroe & Sibly, 1993	$y=0.1931x+1.5005$	$R^2=0.8336$ $p<0.05$

Table 1. Information of organism groups in Alabama and global birds.

Group	Entropy within group	Maximum Entropy within group	Entropy of all species	Maximum Entropy for all species
Fishes	1.107	2.526	2.023	3.727
Amphibians and reptiles	1.116	2.311		
Mammals	1.178	1.887		
Birds	1.471	2.511		
Butterflies	0.615	2.143		
Plants	1.806	3.632		
Global birds	1.682	3.987		

Table 2. Entropy and maximum entropy of families and species in Alabama.

A commonly used least squares technique was used for correlation analysis between $\log_{10}(x_i)$ and $\log_{10}(y_i)$ through linear fitting ($y=ax+b$) by SAS software (SAS Institute Inc., NC, USA). Slope (a) is also called the exponent of power laws or power exponent. The slope a values of different organism groups were compared by T-test (Sokal & Rohlf, 1995). All the tests were considered statistically significant as $p < 0.05$.

Entropy was calculated as the following, which is similar to Shannon entropy

$$Entropy = -\sum_{i=1}^{m} p_i \log_{10}(p_i)$$

m is the number of families,

$$p_i = \frac{s_i}{\sum s_i}$$

s_i is the species number within family i,

$$MaxEnt = -\sum (1/S)\log_{10}(1/S)$$

S is the total species number within a group or overall.

RESULTS AND DISCUSSION

The family-species distribution for each group of organisms in Alabama does follow a power law (Table 1), but the power exponent varies among groups. There is no significant difference for the power exponents among the groups of fishes (0.0873), mammals (0.0985) and plants (0.0803), also between amphibians and reptiles (0.1451) and birds (0.156). The power exponent of butterflies (0.6485) is quite different with others. The power exponent is 0.143 for all combined species and families in Alabama. For global birds, the power exponent is 0.1931, which is significantly different with any (or all) organism group in Alabama.

The entropy within group and overall does not reach or even close to maximum entropy (Table 2). It is only about half of MaxEnt for each group including global birds. They are far away to be evenly distributed or from equilibrium.

The results here confirm the work of Yule (1924) and Burlando (1990) that family-species distribution tends to follow power laws but often show strong deviations from such laws. Yule (1925) considered that the deviations from the power laws were attributed to the fact that the populations had not reached equilibrium. Chu & Adami (1999) indicated that the deviations were time independent and reflected specific environmental conditions and pressures to which the communities under consideration was subjected during evolution; they suggested that power law distributions are statistically inevitable for taxa higher than species. This means that some families under certain environment might produce more species, while others might have limited species. This is known as preferential attachment, which leads to complex networks that have properties different from classical random network theory (Lorimer et al., 2015). Our results do not support Singh et al. (2007) found that the evolutionary process is characterized by a power law with a universal exponent that is independent of the pair of species compared. Disturbances and land use change may dramatically change species and family distribution and cause the deviations in the power laws. The power exponent was considered to be near 1 (Burlando, 1990; 1993). However, in this study the power exponents are much lower than 1. These low values of the exponents may be related to a very low rate of beneficial taxon-forming (or niche-filling) mutations and also self-organized criticality (Chu & Adami, 1999). Spitzer (1964) indicated that the underlying stochastic process responsible for the observed behavior can be explained by a random walk. Same as the entropy measure, which is far less than the MaxEnt within each group or overall. This means that family-species distribution is far away to even distribution or equilibrium.

The similar power exponents in mammals, plants and fishes may indicate that mutualistic interactions in the dynamics of terrestrial and fresh water ecosystems. These multispecies networks (e.g., plant-mammal, plant-fish) and their functional consequences (e.g., food web or similar spatial scales) may constitute for strong coevolution (Thompson, 2005). Similar interactions may also exist for amphibians and reptiles, and birds. The quite different power exponent in butterflies or birds may indicate their relationships possibly exist with only some special plants or landscape (Chen & Feng, 2016). The different power exponents for birds in Alabama and world may indicate that it will be wrong to extrapolate the family-species relationship from a regional scale to global scale.

Studying the macroscopic patterns of family-species distribution in Alabama not only gives theoretical insight into the regional biota, but also provides implications to devise long-term estimations and strategies for biodiversity monitoring and conservation. First, we can use the relationships of family-species distribution in Alabama to identify conservation priority, such as identifying some families with only one or two species and the spatial distribution (Chen, 2008). Second, it is an evolutionary process that some species may become extict or some new species may come out because they are far away from equilibrium. With the local land use change, the evolutionary process may be altered. Third, we need to pay attention to monitoring the emergent properties (e.g., strength of self-organization) of biodiversity under land use change, rather than just single species, such as comparing the hierarchical relationships between family-species distribution by using historical (fossil record) information. It may provide suggestions whether the continuing development in land use change at the state level will affect this hierarchical relationship in biota. Furthermore, it can be used to estimate species number at a large area based on the appeared family number, which may be used as background information. Finally, it may provide a method to study the contribution of major landscape (ecosystems) with more species or family number in biodiversity conservation (e.g., Chen et al., 2005). These areas may be important for biota evolution, especially for research in speciation, extinction and coevolution.

CONCLUSIONS

Characterizing the family-species distribution in Alabama may be helpful to study biodiversity and evolution at mesoscale. This study will provide a quantitative approach for comparing and evaluating hierarchical biodiversity at a large area. If further studies can be conducted at different spatial and temporal scales, they will help to determine the areas with high speciation and coevolution, where should avoid for land use change or major industrial development in order to maintain high integrity of biodiversity. The cost to monitoring all species at a large area could be decreased with the development of citizen sciences program and monitoring technology (e.g., camera traps and drones).

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