Fuzzy mathematical modeling and analysis of the dynamical behaviors of complex ecosystems *

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Abstract. It is very complex to model, study and analyze the dynamical behaviors of the complex ecosystems. Many ecological theoretical problems are based on niche. The niche one species occupies and the relation between niches of different species will directly influence the species’ dynamical behaviors. The discussion of niche has been very important to an ecosystem. Fuzzy set theory gave a new creative method to form the niche of a species. So, a fuzzy niche theory is founded and is applied to explain the relationship between niches’ separating degree and competition of species and study the dynamical behaviors emerging in the competition bio-system. It also analyses the case of the biological synergism in an illustrative Lotka-Volterra competition bio-system based on niches.

Keywords: niche, niches’ separating degree, Lotka-Volterra bio-system, dynamical behaviors, biological synergy

1 Introduction

The ecosystem is a complex system, and many important theoretical problems of ecology are based on the concepts of niche and community. Niche conception has spread all over the whole of ecological study, becoming an important problem in the research and application of ecological system theories. These theories were widely applied to the relationships between species, community structure, species’ diversity and population evolution. Now, the most popular niche concept is Hutchinson’s definition (1957) “n-dimensional hyper-volume niche”[10].

The concept “N-dimensional hyper-volume niche” describe niche quantitatively by the coordinates of the species on n-dimensional resources axis. The coordinates denote the state points of all the ecological factors about species’ survival and multiplication, such as temperature, humidity, altitude gradient, pH value, resource, space-time, competition and so on. But this definition still cannot explain some ambiguity phenomena in the real ecosystems. For example, the relation of a species’ different population growth in different points of every eco-factor is not very clear. Another example, the boundary of the niche is not distinct in real systems[9].

Thanks to the fuzzy set theory as provided by Zadeh in 1965[1] there is a new method to model niche. To an ecological factor, regarding the fitness degree of a species as the membership degree of this eco-factor, the area that the species live is express by a fuzzy set. Then, synthesizing the fuzzy sets of every ecological factor, the fuzzy niche model is founded.

Using niche theory, many dynamical behaviors in ecological system can be explained, such as competition, coexistence, and extinction of species. Fuzzy niche theory makes the niche no longer only be literary but be formulating, and get rid of the ambiguity in real problems. In the formula of niche, many relatives about niche must be considered, for example, the niche width, the niche overlap, and the niches’ separation

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degree. They can be express by fuzzy mathematical formulae, such as the measurement of the niche width and the niche overlap in Yang’s and Piou’s studies[6–8]. They are just those variants that have great influence on the dynamic behavior of species. The value of these variants suggests the relationship of species, embodies biological synergy and competition traits. Study of these relatives may benefit to the explanation of population evolution.

This paper is organized as follows. In Section 2, fuzzy niche model is proposed and used to discuss the relationship between niches’ separating degree and species’ competition. Next, in Section 3, in the L-V competition model in which the population growth is based on resources, the competition coefficients are studied. Following this, in Section 4, a discussion to the dynamical behavior of the model for different niches’ separation degree shows a biological synergy in the competition bio-system. It also shows the influence of the parameters to and the coexisting conditions of the model we simulate by computing. All the work is concluded in Section 5 with a discussion of the results obtained and some possible future directions for related research.

2 Niche theory and competition

Niche is a comprehensive concept. It can be described as the amount of the ecological environment actually occupied by the organism and the organism’s ability to use it. It is a dissipative structure, because it must exchange and circulate material, energy and information with environment. But it is also a fully-exploit dynamic system under certain research conditions. From the geometry meaning, it is an n-dimensional hyperspace, which includes all the ecological factors near by species’ survival and multiplication, such as temperature, humidity, altitude gradient, pH value, resource, space-time, competition and so on. The intersection of these factors describes the individual’s niche. Based on the “n-dimensional hyper-volume niche”, the fuzzy model of niche given in this section gives a synthetic consideration of all the eco-factors besides resource. It provides a theoretical basis to the study of ecological systems. In an ecological system, competition often becomes intense between species when all species need to occupy similar niches and tend to ease when all the niches become more separated. Thus, it is very valuable to study the relationship between separation of niches and competition.

2.1 Fuzzy model of niche

2.1.1 The fuzzy mathematical model of Hutchinson’s “n-dimensional hyper-volume niche”

**Definition 1.** Let \( A \), a vector of the \( n \)-dimensional real space \( R^n \), denote a certain condition of a species’ survival space. The elements in vector \( A = (\lambda_1, \lambda_2, \cdots, \lambda_n) \) denote the coordinates of all the ecological factors about survival and multiplication (biological and un-biological ones) respectively; so nested region \( H (A) \) of \( n \)-dimensional space is the niche occupied by species \( x \).

\[ H (A) \text{ is the Hutchinson’s “n-dimensional hyper-volume niche” of species } x. \]

We know that niche is the ability for a species to actually occupy, exploit, and utilize the ecological environment. So for a certain organism, each factor has an “optimal tolerated range”, which is a fuzzy concept. Using fuzzy number \( \lambda_i (i = 1, 2, \cdots, n) \) denotes the coordinate of factor \( i \). And \( \lambda_i \) is a bounded, closed fuzzy number. \( A_i \) denotes the fuzzy set of the \( i \)-th eco-factor occupied by the species. The membership functions of \( \lambda_i \) to \( A_i \) is defined as:

\[ \mu_{A_i} (\lambda_i) = \begin{cases} 1 & \lambda_i \in [a_i, b_i] \\ L(\lambda_i) & \lambda_i < a_i \\ R(\lambda_i) & \lambda_i > b_i \end{cases} \]

where \( L(\lambda_i) \) is an increasing, left continuous function, and \( \lim_{\lambda_i \to -\infty} L(\lambda_i) = 0, 0 \leq L(\lambda_i) < 1, \) and \( R(\lambda_i) \) a decreasing, right continuous function, and \( \lim_{\lambda_i \to -\infty} R(\lambda_i) = 0, 0 \leq R(\lambda_i) < 1 \) then
\( \Lambda = (\lambda_1, \lambda_2, \cdots, \lambda_n) \longrightarrow H(\Lambda) = (A_1, A_2, \cdots, A_n) \). Now, the nested set \( H(\Lambda) \) is the fuzzy mathematical model of Hutchinson’s “\( n \)-dimensional hyper-volume niche”.

### 2.1.2 The fuzzy model of optimal niche

When \( \mu_{A_i}(\lambda_i) = 1 \), \( \lambda_i \) is “the optimal” one to the population growth of species \( x \). If all the materialized conditions are “the optimal”, then \( \Lambda = (\lambda_1, \lambda_2, \cdots, \lambda_n) \) denote the best state in the optimal niche. On the contrary, if none of the materialized conditions are “the optimal”, \( \Lambda = (\lambda_1, \lambda_2, \cdots, \lambda_n) \) is a sub-optimal coordinate of the species’ niche. Other cases between the optimal niche and sub-optimal niche cannot be given an exactly definition, are fuzzy state. So, the membership function of \( \Lambda = (\lambda_1, \lambda_2, \cdots, \lambda_n) \) to the optimal niche \( V^* \) is defined as:

\[
\mu_{V^*}(\Lambda) = \left\{ \begin{array}{ll}
0 & \text{if } \mu_{A_i}(\lambda_i) \neq 1, i = 1, 2, \cdots, n \\
\Lambda_i = H^{-1}(V) & \text{otherwise} \end{array} \right.
\]

where \( H^{-1}(V) = \{ (\lambda_1, \lambda_2, \cdots, \lambda_n) | H(\lambda_1, \lambda_2, \cdots, \lambda_n) = V \} \), and it can provide the model of the optimal niche of species \( x \) more generally.

**Definition 2.** Let \( n \)-dimensional ecological factor \( \lambda_i (i = 1, 2, \cdots, n) \) be a Fuzzy number, and \( \Lambda^* = (\lambda_1, \lambda_2, \cdots, \lambda_n) \) be the coordinate of ecological factors. Then \( H(\Lambda^*) = V^* \) is the optimal niche of species \( x \). It is a \( n \)-dimensional Fuzzy set, in geometry, an \( n \)-dimensional hyper-fuzzy-volume:

\[
H(\Lambda^*) = (H(\lambda_1), H(\lambda_2), \cdots, H(\lambda_n)),
\]

where \( H(\lambda_i) \) denotes the projective niche of the \( i \)-th ecological factor on the \( i \)-th dimension.

### 2.2 Fuzzy model of separating degree of two species’ niches

In an ecological system, competition often become intensive between species when all species need to occupy similar niche and tend to ease when all the species’ niches are more separated. Thus it is very valuable to study the relationship between the separation of niches and competition. Firstly, let’s see how to denote two niches’ separating degree.

Let \( \lambda_i \) be a special Fuzzy number, the interval number. Denote \( \lambda_i = [a_i, b_i] (i = 1, 2, \cdots, n) \) as ecological amplitude. According to shelldorf’s “law of tolerance”, for every environmental factor, every organism has a tolerant range bounded by an ecological lowest point (or lowest degree) and an ecological highest point (or highest degree), and the range between them is called ecological amplitude. So call \( \lambda_{ij} = [a_{ij}, b_{ij}] \) the ecological amplitude of species \( j \) for \( i \)-th ecological factor. We use formula

\[
m_{ij} = \frac{a_{ij} + b_{ij}}{2}
\]

to denote the mean of \( i \)-th ecological factors endured by species \( j \), and \( n \)-dimensional vector

\[
m_j = (m_{1j}, m_{2j}, \cdots, m_{nj}) = \left( \frac{a_{1j} + b_{1j}}{2}, \frac{a_{2j} + b_{2j}}{2}, \cdots, \frac{a_{nj} + b_{nj}}{2} \right)
\]

to denote the center point of species \( j \)’s niche. So the niche separation of two species \( j \) and \( k \) may relate to \( d = |m_j - m_k| \). If all \( \lambda_{ij} \) denote the resource types utilized by species \( j \), \( d \) is the distance between the mean utilizations of two species. In order that the value of niches’ separating degree be proper, we let \( d \) be divided by the mean of niches’ width of the two species.

When ecological factor \( \lambda_i (i = 1, 2, \cdots, n) \) are interval numbers: let the \( i \)-th dimensional niche’s width \( w(H(\lambda_i)) = b_i - a_i \). As a result, the width of niche \( H(\Lambda) \) that species \( x \) occupy is

\[
\delta(H(\Lambda)) = W \{ w(H(\lambda_1)), w(H(\lambda_2)), \cdots, w(H(\lambda_n)) \} = \left\{ \sum_{i=1}^{n} (w(H(\lambda_i)))^2 \right\}^{\frac{1}{2}}.
\]

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So the niche width for species $j$ and $k$ are $\delta_j = \left\{ \sum_{i=1}^{n} (b_{ij} - a_{ij})^2 \right\}^{\frac{1}{2}}$ and $\delta_k = \left\{ \sum_{i=1}^{n} (b_{ik} - a_{ik})^2 \right\}^{\frac{1}{2}}$ respectively.

**Definition 3.** Let $\delta = \frac{\delta_j + \delta_k}{2}$, then $S_{jk} = \frac{d}{\delta}$ denotes the niches’ separating degree of species $j$ and $k$. Where $d$, $\delta_j$ and $\delta_k$ are given above.

### 2.3 Niches’ separating degree and competition

One species occupies and utilizes its own niche. If there is another species, whose niche overlaps the former species’ niche (that is, the two species will use some similar resources), competition of resources will occur. Owing to the species’ different utilization degrees of different resources—the species usually use the resources near the center part of its niche much more than the ones far from the center part, the competition is moderate when the two species niches are distantly separate, and intensive when the niches are closer. It’s obviously that there is some relation between the niches’ separating degree and the degree of competition. We’ll introduce a formula to illustrate this relation in a real ecological system later.

### 3 Competition models

#### 3.1 Lotka-Volterra competition models

Much of the work in the mathematical modeling of competition to date has been based on the multi-species Lotka-Volterra equations\(^2\), which we write here as:

$$\frac{dx_i}{dt} = x_i \left( r_i - \frac{r_i}{K_i} \sum_{j=1}^{n} \alpha_{ij} x_j \right),$$

where $n$ is the number of species present;

- $x_i$ is the population of species $i$ ($i = 1, 2, \ldots, n$) at time $t$;
- $r_i$ is the ‘intrinsic’ growth rate of species $i$ ($i = 1, 2, \ldots, n$);
- $K_i$ is the population of species $i$ ($i = 1, 2, \ldots, n$) that could exist in the absence of competition (the ‘carrying capacity’ of the environment);
- $\alpha_{ij}$ is the competition coefficients, characterizing competition between species $i$ and $j$ ($i, j = 1, 2, \ldots, n$). It is assumed that $\alpha_{ii} = 1$ (i.e. self-limitation is logistic).

Because $\alpha_{ij}$ and $K_i$ are empirical constants, they are hard to determine. MacArthur and Levin\(^3\) put forward the competition coefficient formulas, which are based on utilization of resources:

$$\alpha_{ij} = \frac{\sum_{s \in S} u_i(s)u_j(s)}{\sum_{s \in S} [u_i(s)]^2} \quad \text{(discrete)}; \quad \alpha_{ij} = \frac{\int u_i(s)u_j(s)ds}{\int [u_i(s)]^2ds} \quad \text{(continuous)},$$

where $u_i(s)$ is the utilization function of species $i$ ($i = 1, 2, \ldots, n$); $s$ is a point of resource axis $S$.

MacArthur’s derivation is based on two sets of differential equations: one describing the population growth of the competitors and one describing the population growth of the resources. His model sidesteps the problem of resource depletion and renewal by assuming that resources are very rapidly renewed compared to the depletion by the competitors. The competitors are assumed to obey

$$\dot{x}_i = x_i c_i \left( \sum_{s \in S} a_i(s)W(s)n(s) - M_i \right),$$

where $a_i(s)$ is the probability that a given member of species $i$ ($i = 1, 2, \ldots, n$) finds and consumes a given individual of resource $s$.
\(W_i(s)\) = the weight of an individual of resource \(s\);
\(n(s)\) = the population size of resource \(s\);
\(M_i\) = the cost of maintenance of an individual of species \(i (i = 1, 2, \cdots, n)\);
\(C_i\) = the factor governing the conversion of units of resources into individuals of species \(i (i = 1, 2, \cdots, n)\).

The resources are assumed to obey a series of logistic equations modified by predation:

\[
\frac{dn(s)}{dt} = n(s) \left\{ \frac{r(s)}{K(s)} [K(s) - n(s)] - \sum_j a_j(s)x_j \right\},
\]

(4)

where \(K(s)\) = the carrying capacity of the environment for resource \(s\);
\(r(s)\) = the intrinsic rate of increase of resource \(s\);
\(\sum_j a_j(s)x_j\) = the number of individuals of resource \(s\) depleted by predation by the competitors.

Assuming that the system would be at or near equilibrium, let \(\frac{dx_i}{dt} = 0\), \(\frac{dn(s)}{dt} = 0\), from equations (3) and (4), we can get:

\[
\left[ \sum_{s \in S} a_i(s)W(s)K(s) - M_i \right] - \sum_j \left[ \sum_{s \in S} \frac{k(s)W(s)}{r(s)} a_i(s) a_j(s) \right] x_j = 0.
\]

(5)

Comparing this to the equilibrium conditions for (1):

\[
\frac{dx_i}{dt} = 0, \quad x_i \left( r_i - \frac{r_i}{K_i} \sum_j \alpha_{ij}x_j \right) = 0, \quad K_i - \sum_j \alpha_{ij}x_j = 0,
\]

and insure that \(\alpha_{ii} = 1\), we divide equations (5) by \(\sum_{s \in S} \frac{K(s)W(s)}{r(s)} (a_i(s))^2\), getting the formula

\[
\begin{cases}
K_i = \sum_{s \in S} a_i(s)W(s)K(s) - M_i \\
\sum_{s \in S} \frac{K(s)W(s)}{r(s)} (a_i(s))^2 \\
\alpha_{ij} = \sum_{s \in S} \frac{K(s)W(s)}{r(s)} a_i(s) a_j(s) \end{cases}
\]

(6)

From (2) and (6), we get the utilization function of species \(i (i = 1, 2, \cdots, m)\),

\(u_i(s) = \sqrt{\frac{K(s)W(s)}{r(s)}} a_i(s)\).

In the real ecological system, the determination of \(a_i(s)\) is very difficult, needing a large quantity of statistical data. So we assume that the probability of the utilization of resource \(s\) is normally distributed:

\(a_i(s) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(s - m_i)^2}{2\sigma^2}}, \) where \(\sigma = \frac{\delta}{4}\), \(\delta\) denotes the niche’s width of species \(i\).

Thus, the probability of the utilization of the resource exceeding ecological amplitude \([m_i - \frac{\delta}{2}, m_i + \frac{\delta}{2}]\) is \(P(|s - m_i| > \frac{\delta}{2}) = P(|s - m_i| > 2\sigma) \approx 0.0455\). This simply reflects that the species seldom use the resources far from the center part of its niche.

I.e. if we accept \(C = \frac{1}{\sqrt{2\pi}\sigma} \sqrt{\frac{K(s)W(s)}{r(s)}}\), then \(u_i(s) = Ce^{-\frac{(s - m_i)^2}{2\sigma^2}}\).

Where \(m_i\) = the mean of all resource types used by species \(i (i = 1, 2, \cdots, n)\), that is, species \(i\)’s position on the resources curve;

\(\sigma = \) the standard deviation of the utilization curves, assumed the same for all \(i\).

So that the competition coefficients:

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\[
\alpha_{ij} = \frac{\int u_i(s)u_j(s)ds}{\int |u_i(s)|^2ds} = \frac{\int C^2e^{-\frac{1}{2}\left[(s-m_i)^2 + (s-m_j)^2\right]}ds}{\int C^2e^{-\frac{(s-m)^2}{\sigma^2}}ds},
\]

(7)

Especially, when \( C \) is a constant, i.e. it is the same to all \( s \) of the resource axis \( S \). This result can be simplified as below:

Let \( d = m_j - m_i \) (assuming without loss of generality that \( m_i \leq m_j \)), (7) becomes

\[
\alpha_{ij} = e^{-\frac{d^2}{4\sigma^2}} = e^{-\frac{1}{4}\left(\frac{d}{\delta}\right)^2} = e^{-4\times\left(\frac{d}{\delta}\right)^2},
\]

(8)

and \( \alpha_{ij} = \alpha_{ji} \). From this formula, as soon as the positions of competitive species are given, the niche separation \( d \) and the niche width \( \delta \) can be calculated, so the competition coefficient can be determined.

In chapter 2, we discussed the relationship between niches’ separating degree and species’ competition. Formula (8) verifies this result. It shows that the competition coefficient exponentially increases as the niches’ separating degree decrease.

Basing on the discussion above, the two-species Lotka-Volterra competition model can be written as

\[
\begin{align*}
\dot{x}_1 &= \frac{r_1}{K_1}x_1(K_1 - x_1 - \alpha x_2) \\
\dot{x}_2 &= \frac{r_2}{K_2}x_2(K_2 - x_2 - \alpha x_1)
\end{align*}
\]

(9)

where \( \alpha = e^{-4\times\left(\frac{d}{\delta}\right)^2} \), and \( \frac{d}{\delta} \) denotes the niches’ separating degree of the two species considered in (9). This can be give by the relation of the two species’ niche.

Next, the relation between the niches’ separating degree and competition will be shown in a real bio-system.

4 Dynamical phenomena in competition bio-system

In biological systems, whether competition will lead to extinction or coexistence is still a very interesting problem. This will be influenced by the intense degree of the competition. When the intense of competition reach a certain degree, the system also can show a synergistic mechanism: different species compete, but evolve as integration, showing non-equilibrium regular periodic oscillation.

In section 2 and 3, we show that competition between two species become intensive as the niches’ separating degree decreases. To interpret the influence of this on the species’ evolution of competition based on niche, in this section we show the dynamic behavior in a competitive bio-system where the niches’ separating degree and other parameters change, using the model which system (9) described.

4.1 Dynamical behaviors emerge as the niches’ separating degree changes

At first, we study system (9) under the condition: \( r_1 = 0.22, r_2 = 0.06; K_1 = 13, K_2 = 8 \). These are two competitive species (\textit{Saccharomyces cerevisiae} and \textit{Schizosaccharomyces kephir})’s intrinsic growth rates and ‘carrying capacities’ of the environment. We give the initial population values of two species: \( x_{10} = 8, x_{20} = 5 \). These values show species 2 is at a disadvantage in competition because it has a lesser intrinsic growth rate and lesser ‘carrying capacity’ of the environment, and finally, because its initial population number is less than that of species 1.

By means of computer simulation, we find the system will show several different increasing patterns as the niches’ separating degree \( \frac{d}{\delta} \) decreases (or competition coefficient \( \alpha \) increases), as the following figures demonstrate.

When the value of \( \frac{d}{\delta} \) is very big (more than 1), the competition barely exists. The two species grow respectively, and the population numbers can reach their own ‘carry capacities’, see Fig. 1. Because the interspecies competition still exists in species 1, which has higher growth rate, the growth of species 1 shows periodicity in this figure.
When the value of $\frac{d}{\delta}$ is relatively big ($\geq 0.5085$), i.e. the value of $\alpha$ is less than or equal to 0.3555, the two species will coexist, see Fig. 2 ∼ 4. In this case, because the niches’ separating degree is relatively high, competition between two species is not obvious at the beginning, and both species increase. When the population number reaches a certain value, then competition for niches become intensive, so the number begins unstable increasing—oscillating near a relatively steady value. The steady values the two species’ population numbers oscillate near by becomes small as $\frac{d}{\delta}$ decreasing—the population of species 1 is always more than initial value but the population of species 2 decreases from more than to less than the initial value. From these figures, we also can see another phenomenon—because competition becomes more and more intense as $\frac{d}{\delta}$ decreases, the increase of the population at the beginning gradually eases down. The increase of species 2’s population even shows a tendency of decrease.

When the value of $\frac{d}{\delta}$ is less than 0.5085 but more than 0.35, i.e. the value of $\alpha$ is more than 0.3555 but less than 0.6126, two species will coexist, see Fig. 5 ∼ 6. Because the niches’ separating degree is relatively high, competition is intense at the beginning. Species 2 is inferior in competition, so the species 1 increases and species 2 decreases initially. But when the population number reaches a certain value, the number begins unstable increasing—oscillating near a relatively steady value. And as the value of $\alpha$ increases, the species 2 becomes more and more inferior in competition and its population number becomes less, so the periodical phenomena in its population growth become more and more weak. At the same conditions, the population growth of species 1 becomes more and more regular, and the final steady value more and more close to the species’ ‘carrying capacity’ of the environment.

When the value of $\frac{d}{\delta}$ is relatively small (less than 0.35), i.e. the value of $\alpha$ is more than 0.6126, species 1 will exist and special 2 will eventually become extinct, see Fig. 7. At the beginning, the population number of species 1 increase and the population of species 2 decrease. But at a certain time, species 2 begins irregularly decreasing to extinction and species 1 oscillate near its ‘carrying capacity’ of the environment. During the growth of species 1, the quasi-periodical phenomenon due to interspecies competition appears very intensively. But from the tendency the figures show, we can speculate that the growth of species 1 will be relatively regular and steady. In this case, the two species have similar requirements, so the most efficient species will eliminate its competitor.

From these figures, we can find that if the two species could coexist, they would evolve as integration, increasing and decreasing at the almost identical times. They get synergistic evolution by competition.
And considering long-term changes, their growth are relatively regular periodic or quasi-periodic. These two species will coexist and equation (9) will reach a stable equilibrium\cite{4, 5}.

When we change the value of the parameters in system (9), we find the population growth tendency’s change as $\frac{d}{\delta}$ changing has little relation to the change of intrinsic growth rate and the initial population number of two competitive species, but has much relation to the ‘carrying capacity’ of the environment. If the ‘carrying capacity’ of the environment does not change, the general change tendency will not be qualitatively affected, only the critical value will change. Even the critical value won’t change if we only change the intrinsic growth rate. So it is reasonable for us to regard the ‘carrying capacity’ of the environment as the species’ ability...
Fig. 4. the population growth change of two species as $\delta = 0.55$, i.e. $\alpha \approx 0.298$

Fig. 5. the population growth change of two species as $\delta = 0.5$, i.e. $\alpha \approx 0.368$

to compete. And with the value of $\frac{d}{2}$ decreasing, the competition inferiority due to low ‘carrying capacity’ becomes obvious.

5 Conclusion

The realized living environment of a species is influenced by the degree of environment development and utilization, which shows that:

(1) The process of species’ evolution;

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(2) The communication between species and the outer space;
(3) The ability of its survival and fitness.

Competition emerges when different species need to use similar resources, i.e. they occupy close niches; it becomes more intense when the distance between niches is smaller. The niches’ separating degree based on fuzzy niche theory well embodies this distance. The competition coefficient based on the utilization of resources in section 3 embodies the relation between niches and competition. The result of computer simulation in section 4 demonstrates the relation: if the niche’s separating degree is moderate, the two competing
species will enter synergistic evolution; if the niche’s separating degree is very large, the two species will
growth respectively; if the niche’s separating degree is very small, the two species won’t coexist. There are
still some problems that need to be studied. For example, how does competition influence species’ utilization
of environment, and how deep it can influence the species’ niche. Because all the work we do is in a simulated
ecological system, comparing them to actual ecological communities remains a problem for future research.

References

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46–51.