Applied Mathematics and Computation 320 (2018) 425–436

Contents lists available at ScienceDirect

Applied Mathematics and Computation

journal homepage: www.elsevier.com/locate/amc

Balancedness among competitions for biodiversity in the cyclic structured three species system

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ARTICLE INFO

Keywords:
Cyclic structured three species
Symmetry breaking of interspecific competition
Balancedness of competitions
Biodiversity

ABSTRACT

Balancedness among species interactions may be an important key to understand species biodiversity. Biodiversity among species is usually promoted by competitions which can occur between two different species or among the same species. In this paper, we investigate how symmetry breaking of interspecific competitions can affect biodiversity on cyclic structured three species which may compete with themselves. From theoretical and numerical results of the deterministic system, we found that the symmetry breaking of interspecific competitions on the self-competitive species system can lead the emergence of new survival states in which are stable. Further, we figured out that these diverse survival states can be influenced by the moderate balance between interspecific and intraspecific competitions which is uncovered numerically.

1. Introduction

One of the fundamental keys to species coexistence and biodiversity is a competition. In ecology, there are two types of competitions which can either promote or hinder biodiversity [1,2]: interspecific among individuals from different species (e.g. predator-prey interaction) and intraspecific among individuals in the same species (e.g. cannibalism) which occur for same essential life-sustaining resources [3–10]. Such competitions can also occur when individuals fight each other for mating opportunities as in side-blotched lizards in California [11]. In the past decade, there were studies of the effect of intraspecific competitions on biodiversity, such as the experimental finding that competitions tend to drive disruptive selection [12], enhanced host survival through intraspecific competitions between co-infecting parasite strains [13], relativeness between predation and competition [14], and directional selection of certain fish species [15,16].

Cyclic competitions, which have been observed in real ecosystems [11,17–19] have been widely studied for explaining the mechanisms of biodiversity [20–42]. Most existing works show the emergence of spirally entangled self-organized pattern formations on spatially extended systems and biodiversity such as transition induced by individual mobility [27–33], diverging fluctuations [34], intraspecific competitions [35,36], continuous space [37], basins of the coexistence states [38,39], local habitat suitability [40], symmetry breaking by niche construction [41], cyclic dominance arising in human cooperation [42], heterogeneous invasion rates [43–45], nonuniform microscopic dynamics induced by zealots and spillovers [46,47], and pairwise and group-level interactions [48].

Under the framework of cyclic competitions, symmetry breaking has received wide attention because the asymmetric scenarios can be diverse. For example, if the dispersal rates of all species are similar to each other, the coexistence takes

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https://doi.org/10.1016/j.amc.2017.09.047
0096-3003/

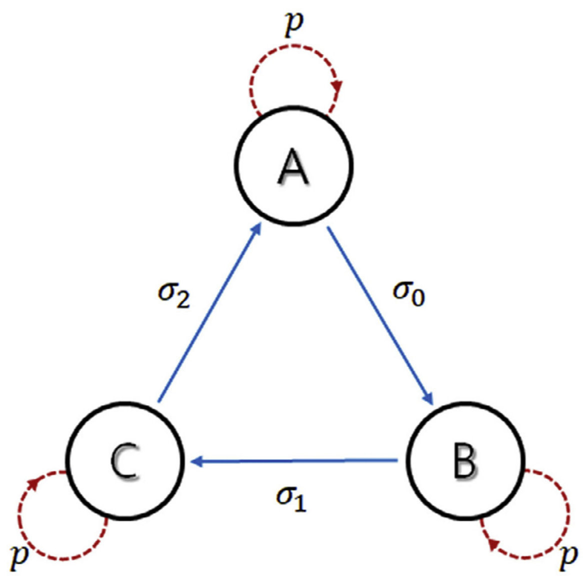

Fig. 1. Schematic illustrations of two types of competitions among cyclic structured three species. In each species, red dashed loops indicate intraspecific competitions occurred with a rate p. Among three species, interspecific competitions (blue straight lines) can occur with different rates, σ_0, σ_1 and σ_2 for pairs of species (A, B), (B, C), and (A, C), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the form of spiral waves or target waves [27,31,32] while it does not appear under the unequal mobility. In systems of phytoplankton [18] and microbes [19], advection and diffusive transportation can interact with the environment and form a complex interplay of diverse factors dictating symmetry breaking [49]. Although the symmetry breaking has been issued, related existing works have been considered symmetric interaction structures where any interactions such that competitions or reproduction are equally considered for any different species due to the complexity of systems [50–59].

The important role of intraspecific competitions for biodiversity has been uncovered in the basic cyclic competing system [35]. When cyclically competing three species do also compete with themselves, the coexistence of all species is more promoted as the strength of intraspecific competitions is enhanced. In this regard, intraspecific competitions have been focused as a key factor for maintaining biodiversity even in cyclic structured population systems.

Motivated from [1,2,14,35], we may ask what happens in cyclic structured self-competitive populations by nonuniform interspecific competitions and how the balance between interspecific and intraspecific competitions affects biodiversity. In this paper, we investigate the effect of nonuniform interspecific competitions for biodiversity in the cyclic self-competitive three species system. In a simple approach and to make an unbiased comparison, we consider that intraspecific competitions for all species will be occurred with a same rate. Briefly, we found two significant results: (a) Diverse survival states can be driven by nonuniform interspecific competitions, and (b) these diverse states can be induced from the balance between two competitions.

2. Model

We consider three cyclic structured self-competitive three species A, B and C which are usually described by the rock-paper-scissors game [20,27,28]. Under the assumption of nonuniform interspecific competitions, basic interactions among species occur according to the following general rules:

$$AB \xrightarrow{\sigma_0} A\varnothing, \quad BC \xrightarrow{\sigma_1} B\varnothing, \quad CA \xrightarrow{\sigma_2} C\varnothing, \tag{1}$$

$$AA \xrightarrow{p} A\varnothing, \quad BB \xrightarrow{p} B\varnothing, \quad CC \xrightarrow{p} C\varnothing, \tag{2}$$

$$A\varnothing \xrightarrow{\mu} AA, \quad B\varnothing \xrightarrow{\mu} BB, \quad C\varnothing \xrightarrow{\mu} CC, \tag{3}$$

where $\varnothing$ stands for a vacancy. For interspecific competitions (1), any two different species compete with different rates σ_0, σ_1, and σ_2. Intraspecific competitions (2) occur with the same rate p for all species which are illustrated in Fig. 1. The reproduction (3) can be allowed when any species have a chance to reproduce within free spaces.

To get global aspects of dynamical behaviors, we may approach by using ordinary differential equations in mean-field manners. Let $a(t)$, $b(t)$ and $c(t)$ be the density of species A, B and C at time t, respectively. A total density of three species at