Applied Mathematical Modelling 39 (2015) 574–585

Contents lists available at ScienceDirect

Applied Mathematical Modelling

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

Evolutionary analysis of a predator–prey community under natural and artificial selections ☆

Xinzhu Meng [a,b,*], Rui Liu [a,b], Lidan Liu [a,b], Tonghua Zhang [c]

[a] College of Mathematics and Systems Science, Shandong University of Science and Technology, Qingdao 266590, PR China
[b] State Key Laboratory of Mining Disaster Prevention and Control Co-founded by Shandong Province and the Ministry of Science and Technology, Shandong University of Science and Technology, Qingdao 266590, PR China
[c] Department of Mathematics, Swinburne University of Technology, PO Box 218, Melbourne, VIC 3122, Australia

ARTICLE INFO

Article history:
Received 31 August 2013
Received in revised form 15 May 2014
Accepted 18 June 2014
Available online 1 July 2014

Keywords:
Predator–prey model
Adaptive dynamics
Evolutionary stable strategy
Natural selection and artificial selection
Size-selective harvesting

ABSTRACT

This paper investigates the evolutionary impacts of size-selective harvesting and size-dependent competition in predators on an evolving trait of predator individuals (e.g. body size and maturation age) in a predator–prey model. By using population dynamics and adaptive dynamics, we obtain the evolutionary conditions allowing for evolutionary branching and continuously stable strategy under asymmetric competition in predators for natural selection and size-dependent harvesting for artificial selection. The evolution of polymorphism is explored by numerical analysis and simulations. It is shown that high levels of sequence polymorphism may work up during adaptive evolution that leads to biological diversity. First, increase in competition among predators can result in rapid evolution towards larger body size or maturation age, but harvesting has an opposite effect. Second, competition can make for evolutionary branching, while harvesting can go against evolutionary branching and promote evolutionary stability. Last, from an evolutionary point of view, that competition can promote species diversity among predator populations, however, harvesting has an opposite effect.

1. Introduction

We know that, in recent years, great changes have taken place in the phenotype traits of many species, such as small body size and earlier maturation [1–3], and we are also aware that natural selection and artificial selection play an important role in phenotype traits' evolution processes. However, they have different consequences of the phenotype traits [4].

Natural selection is good for improving individuals' adaptability, and individuals which have high fitness values survive. Thus it is not surprising that the mutant with a lager body size is easier to survive under natural selection. When competing for limited resources, the larger individuals have competition advantage to survive relative to its small contestant [5], which is a phenomenon known as asymmetric competition, for example, the bigger predator can catch more prey. The natural selection due to the asymmetric competition is a persistent and continuing phenomenon in nature [6].

☆ Supported by the National Natural Science Foundation of China (Nos. 11371230; 61304080), Shandong Provincial Natural Science Foundation, China (No. ZR2012AM012), a Project of Shandong Province Higher Educational Science and Technology Program of China (Grant no. J13LI05), the SDUST Research Fund for Scientific Research Team "Systems Biology and Dynamics".
* Corresponding author. Tel.: +86 13953230761.
E-mail addresses: mxz721106@sdust.edu.cn (X. Meng), tonghuazhang@swin.edu.au (T. Zhang).

http://dx.doi.org/10.1016/j.apm.2014.06.016
0307-904X/

Artificial selection happens all the time nowadays, for example, size-dependent harvesting where large individuals of a particular species are preferentially taken, as a consequence a rapid evolution of smaller body mass occurs in both terrestrial and marine resources [7,8]. Therefore, as a phenotype trait, body size will be taken as an object of study. Human-induced evolution due to the artificial selection can be fast and harmful, which has been confirmed by both theoretical and empirical studies [9,10].

The aim of this paper is to explore the influence of size-selective harvesting predators and competition in predators on evolutionary changes in adaptive dynamics of a predator–prey system. In particular, we will seek the conditions, under which evolutionary branches in predator phenotype and the mutant predator stably coexists with the resident predator at a much longer timescale of evolution. Moreover, after the primary branching in predator phenotype, we further investigate the final evolutionary state of such a dimorphic predator population and show an attractive dimorphism can proceed to undergo a secondary branching which leads to a polymorphic population.

The rest of the paper is organised as follows. Next section, a predator–prey type of model is proposed. Population dynamics and evolutionary dynamics are investigated and the invasion fitness for the mutant predators is derived in Section 3. We then study the influence of competition for natural selection and harvesting for artificial selection on evolution changes in the phenotype traits in Section 4. Moreover, Section 4 also discusses the dimorphic coexistence and the coevolution of population model with two resident predators. Finally, we conclude the paper in Section 5 with discussions.

2. The mathematical model

Well known facts are that

- individuals with large body size (maturation age) have not only the higher probability to win the competition but also the higher capture rates;
- it is common in nature that the large individuals of a particular species are preferentially taken.

In virtue of the importance of body size (maturation age) in size-selective harvesting and in determining interactions between competing species, we regard body size (maturation age) as the phenotype trait. And in this study, we consider effects of the trait on (a) the capital capture rate, (b) the harvesting rate and (c) the competition coefficient in the predator population. Then, we reach a model governed by

$$\begin{cases} N'(t) = rN\left(1-\frac{N}{k}\right) - \sum_{i=1}^{n}\beta(x_i)NP_i, \\ P_i'(t) = \theta\beta(x_i)NP_i - dP_i - h(x_i)P_i - \sum_{j=1}^{n}a(x_i-x_j)P_iP_j, \end{cases} \tag{1}$$

where $N(t)$ is the prey density and $P_i(t), i = 1,2,\ldots,n$ denote the population densities of the predators at time t; x_i is the phenotype trait of the predator population P_i; n is the number of strategies which present in the population; r is the intrinsic growth rate of $N(t)$; k denotes the biggest environmental intake capacity; $\beta(x_i)$ and θ stand for the capital capture rate and the transform rate, respectively; d is the death rate of the predator population; $h(x_i)$ is the harvest rate of the predator population $P_i(t)$; the competition coefficient, $a(x_i - x_j)$, indicates the effect of strategy x_j on strategy x_i.

3. Adaptive dynamics

In this section, we shall derive the invasion fitness of a rare mutant predator in a resident-settled environment and seek the general conditions for evolutionary branching and evolutionary stable strategy. We start with a singe resident population and then proceed with higher level dimorphic populations. It assumes that the mutation occurs infrequently when the resident populations are settling on their demographic attractor [11]. In addition, when a mutant with a slightly different strategy appears in a resident system, its population density is assumed to be so rare that it has a negligible effect on the resident populations. Thus the invasion fitness of the mutant is entirely determined by the demographic attractor of the resident strategies.

3.1. Monomorphic adaptive dynamics

In this subsection, we first develop the population dynamics with a prey and a resident predator that has a trait x; then we seek the invasion fitness that to be used to explore the evolutionary dynamics; and at last, we seek the conditions under which the resident predator undergoes evolution branching.

For a predator population of a single resident strategy x, population model (1) becomes

$$\begin{cases} N'(t) = rN\left(1-\frac{N}{k}\right) - \beta(x)NP, \\ P'(t) = \theta\beta(x)NP - dP - h(x)P - a(0)P^2. \end{cases} \tag{2}$$