Chaos, Solitons and Fractals 179 (2024) 114449

Contents lists available at ScienceDirect

Chaos, Solitons and Fractals

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

Dynamics of a two-prey one-predator model with fear and group defense: A study in parameter planes

Ruma Kumbhakar [a], Mainul Hossain [a,b], Nikhil Pal [a,*]

[a] Department of Mathematics, Visva-Bharati, Santiniketan 731235, India
[b] Department of Mathematics, Victoria Institution (College), 78-B, A. P. C. Road, Kolkata 700009, India

ARTICLE INFO

Keywords:
Fear
Group defense
Chaos
Isospike diagram
Periodic windows
Coexisting attractors

ABSTRACT

Ecosystems are profoundly affected by the predator–prey relationship. During foraging, prey animals balance food and safety demands, and adopt anti-predator behaviors to increase their survival chances. Many prey animals take steps to reduce their predation risk, including moving to low-risk and less profitable areas, becoming more vigilant, and altering their reproductive strategy. Some prey animals employ the strategy of group defense to reduce their chances of being preyed upon by predators. In the present study, we consider a two-prey one-predator model, where one prey species shows group defense against the predator population while the other does not. We explore the complex dynamics of the system in different parametric planes using isospike and Lyapunov exponent diagrams. We observe several kinds of organized periodic structures, coexistence of different types of attractors, both spike-doubling and spike-bubbling routes to chaos, etc. We also investigate how fear and group defense parameters influence the system's dynamics and play roles in the survival and extinction of the species.

1. Introduction

The interaction between predator and prey has remained a central theme in theoretical ecology and evolutionary biology for decades, and mathematical models have contributed significantly in advancing the understanding of these complicated interactions. Empirical observations concerning predator and prey provide us with helpful information about the interaction between them. However, an analytical formulation of an appropriate model and systematic analysis are required to validate the experimental findings and generalize the outcomes from a mathematical perspective. In the past few years, numerous mathematical models have been developed to describe and explain predator–prey interactions from various viewpoints [1].

In predator–prey interaction, predation plays an important role as a species' survival depends on it. Thus, an obvious question arises: how do predators affect the prey populations? Predators can affect their prey in two ways: directly and indirectly [2]. In a direct way, predators actively attack and kill their prey, leading to a decrease in prey numbers. This direct predation is clearly observed in natural settings [3]. In an indirect way, plenty of behaviors of prey species change due to the mere presence of predators [2,4]. Studies have demonstrated that indirect effects often exert a more significant influence on controlling the dynamics of the system than direct predation [5–8].

Fear is an indirect effect that manifests as behavioral and physiological changes among prey populations when predators are present. Prey adapt their behavior in response to fear of predators to boost their survival likelihood. As a result, prey populations implement various anti-predator strategies, such as enhancing vigilance, foraging less, avoiding high-consumption and high-risk regions, altering reproductive physiology, and changing their habitat to low-risk locations [9–13]. For instance, birds leave their nests upon hearing the sounds of their predators [14]. Bluegill sunfish (*Lepomis macrochirus*) shift their habitats to safer areas because of the predation risk posed by largemouth bass (*Micropterus salmoides*) [15]. Elk's (*Cervus canadensis*) reproductive physiology alters because of the fear of wolves (*Canis lupus*) [16]. It is worth noting that while such anti-predator strategies might be advantageous in the short term by increasing the survival of prey individuals, they have unintended side effects in the long term. Zanette et al.'s experimental work on song sparrows (*Melospiza melodia*) is a direct evidence in this regard [17]. They observed that fear of predators changed the nest site selection strategies, flight distance, and food consumption patterns of the song sparrows, which led to a decrease in egg production, resulting in a significant 40% decline in number of offsprings. Inspired by experimental works on fear effect, Wang et al. first formulated and studied a mathematical model to describe the impact of fear on the prey population [18]. During the past few years,

* Corresponding author.
E-mail address: nikhil.pal@visva-bharati.ac.in (N. Pal).

https://doi.org/10.1016/j.chaos.2023.114449
Received 19 August 2023; Received in revised form 28 December 2023; Accepted 31 December 2023
Available online 18 January 2024