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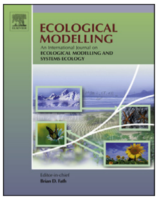

Physiological responses of fish under environmental stress and extension of growth (curve) models

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ABSTRACT

The physiological responses of fish to the environmental stress have been broadly classified into three categories, namely, primary, secondary and tertiary. We have proposed two extended growth curve models considering the physiological responses of fish due to various stressors. We illustrate the proposed models based on a fish growth data where tree shading effect on the water and the habitat alteration play a significant role. The tree shading effect produces different ecological niche in the water ecosystem. We consider the two stressors viz. heat-shock and deficiency of dissolved oxygen, originates from the habitat alteration and tree shading effect issues. The proposed models can capture the different forms of species fitness and thus quantify the stress effect accurately in comparison with the standard models. This quantification is achieved by introducing an additional parameter with the existing mathematical forms of Gompertz and logistic function. We extend these deterministic models by incorporating the random environmental influences. We study the mathematical properties of the proposed models and compute some important characteristics, namely, the point of inflections, asymptotic size, etc. We use the nonlinear least squares method to estimate the model parameters. We also discuss the existence and consistency of the estimates. The stochastic models appeared to give significant improvement over the deterministic case.

1. Introduction

The fish community displays a wide variation in their physiological responses to various forms of stress effects (Bonga, 1997; EL-Khaldi, 2010). The physiological responses of fish to the environmental stress have been broadly classified into three categories, namely, primary, secondary and tertiary (Barton, 2002; Wu et al., 2017). The primary response represents the initial neuroendocrine response which includes the release of catecholamines from chromaffin tissue (Randall and Perry., 1992; Reid et al., 1998), and the stimulation of the hypothalamic–pituitary–interrenal (HPI) axis, which ultimately culminates in the release of corticosteroid hormones into circulation (Donaldson, 1981; Mommsen et al., 1999; Wu et al., 2017).

The changes in the ions and their metabolite levels of plasma and tissue, hematological features, and heat shock or stress proteins (HSPs), are typical features of the secondary responses (EL-Khaldi, 2010). These phenomena are related to the physiological adjustments of fish such as metabolism, respiration, acid–base status, hydromineral balance, immune function and cellular responses (Bonga, 1997; Iwama et al., 1998; Mommsen et al., 1999).

Additionally, in response to the stress effect, the overall performance of the fish, such as changes in growth, resistance to disease, the metabolic scope for activity, etc. is designated as the tertiary responses (Wedemeyer and McLeay, 1981; Wedemeyer et al., 1990). The classification as described above is simple, however, depending on the magnitude and duration, stress may affect fish at all levels of the organization, from the molecular and biochemical (levels) to the population and community. A misconception among the fishery biologists is that the stress is most commonly detrimental to the growth of fish (Barton, 2002; Wu et al., 2017). But, this is not necessarily the case for all natural situations (Bonga, 1997; Barton, 2002; Wu et al., 2017).

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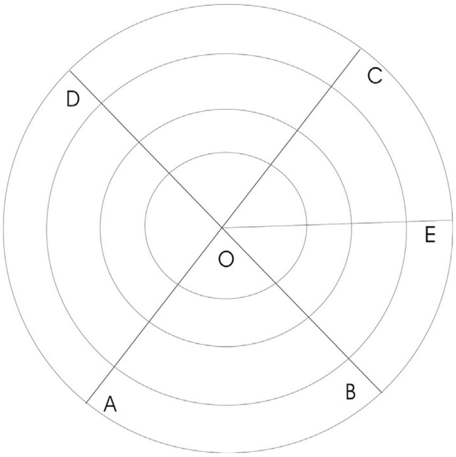

Fig. 1. Circular layout model: OA, OB, OC, OD are the four different directions (can be assumed as Locations A, B, C and D respectively). Intersection points of four concentric circles with the lines OA, OB, OC and OD are the positions of the hoopnets.

Note that the primary and secondary responses are the proxies of changing internal mechanism of fish due to stress, whereas, in comparison, the external changes are reflected through the tertiary responses (Barton, 2002). Hence, any (the) change in the growth trait an important reflector of tertiary responses, whereas the stress effect (either detrimental/incremental) is a good indicator of the primary and secondary responses. So the primary and secondary responses should be considered as key factors while modeling species growth under stress condition.

In modeling species growth through density-dependent model viz. logistic, Richards, von-Bertalanffy, etc., the relative growth rate (henceforth, RGR) is a decreasing function of size (Verhulst, 1838; Gompertz, 1825; Von Bertalanffy, 1960; Richards, 1959; Tsoularis and Wallace, 2002). In ecology, this RGR function is considered as a proxy of species fitness. So in an ideal situation, the species fitness must be a decreasing function of size. This fitness is influenced by the primary and secondary responses while the stress effects act on the species, and the ideal situation is perturbed. Under this situation, the overall fitness, a proxy of the tertiary response, can be represented as the combined effect of ideal species fitness and the primary–secondary responses of the species.

In this article, we develop two new growth curve models by incorporating the physiological responses of fish due to stress effect. We further extend our models for the stochastic environment. We validate the models in light of a fish growth data under natural environmental stressors such as oxygen deficiency and habitat change.

We organize the rest of this article as follows. We first describe a fish growth data under the natural environmental situation in Section 2. We propose two deterministic fish growth models for stress effect and extend these models under stochasticity in Section 3. We have discussed the mathematical properties of the models in Section 4 and in Section 5 we have validated the proposed models with the fish data. We discuss various numerical results in Section 6.

2. The data

A real-life experiment was performed in a pond of Indian Statistical Institute (ISI), Kolkata, to study the adaptability of fish against various stressors under natural conditions. There were four locations in a circular layout model (Fig. 1), namely A, B, C, and D. Four hoopnets were placed in each location. There was no tree shading effect in Location A but in Location B; there was a partial tree shading effect due to a small bush. However, at Locations C and D there was heavy tree shading effect due to big trees and Brick's buildings. In this setup, we have mainly two environmental stressors. One is the deficiency of the dissolved oxygen status due to less photosynthesis by the phytoplankton in Locations C and D where penetration of sunlight is restricted. Our fish samples are reared in a fish farm before we placed these in four locations of the experimental pond. It is a clear case of habitat alteration which we treat as another environmental stress factor (Wedemeyer, 1980).

We collected the initial fish samples from the Fish Farm of Kalyani, West Bengal, India, where they were reared under the same environmental conditions. We finally placed the samples in the hoopnets at ISI experimental pond where they were confined within the hoopnets and not allowed to move anywhere in the pond. The mesh sizes of the nets used in the hoopnets are designed in such a way so that it is capable of allowing free plankton movement. Each hoopnet contained a population of hundred fishes with approximately the same age and size (counting from the hatching period). The detailed description of the experiment is available in Bhattacharya (2003); Bhowmick et al. (2014); Bhowmick and Bhattacharya (2014).

We have chosen the fresh water fish *Cirrhinus mrigala* for our experimental species as it has better adaptability power in adjusting the new environment than the other two major carps viz. *Labeo Rohita* and *Catla Catla*. With the help of a "multichannel analyzer", carrying in an experimental boat, the readings of the water-quality parameters were recorded. For measuring the length, we visited each hoopnets by an experimental boat and took the length measurement of each fish by an accurate metal scale very quickly so that we can return the live sample immediately to the corresponding hoopnets. We also recorded the weight of the fishes and the reading of some water-quality parameters, but these are not used in this article.

We recorded the sizes (length) of 12 fishes for 12 consecutive time points, a constant interval of time, i.e. once in a week (four times in a month). No food was provided to the fishes from any external sources, and they were allowed to grow in the natural environment. We can treat these fishes confined within the four hoopnets in each location as four separate populations. The length measurement was taken by laying the fish on a board with a movable cross hair above it, attached to an indicator running along a scale. We took the natural tip length as a measure of the length of the fish. The "natural tip length" is the length between the tip of the snout (or of the lower jaw when the mouth is closed, which ever protrude further; near the anterior end) and the tip of the longest lobe of the tail when held in a natural position; near the posterior end. Some other commonly used length measures are standard length, median length or fork length, total length or extreme tip length and posterior-hypural length. We collected the data on 12 fishes over 12-time points at four locations. The summary of raw data is available in Appendix A.

3. Model formulation

The relative growth rate (RGR) is considered as a proxy of the species fitness. Usually, in the absence of stressors, the natural species fitness is a decreasing function of size, which is captured by the density-dependent term of the standard growth laws, such as logistic, Gompertz, von-Bertalanffy, Richards, etc. (Verhulst, 1838; Gompertz, 1825; Von Bertalanffy, 1960; Richards, 1959; Tsoularis and Wallace, 2002). However, in the presence of stressors, the primary and secondary responses are accountable for changing the fitness function. The first two responses must be a function of the duration of stress acting on the fish. Tertiary or whole-animal changes in performance, such as in growth, disease resistance, can result from these primary and secondary responses (Barton, 2002).