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Comment

Species extinction in different time scales Comment on "Knowledge gaps and missing links in understanding mass extinctions: Can mathematical modeling help?" by Ivan Sudakow et al.

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A variety of mathematical models have been studied successfully in population dynamics for biological problems [3,13,26], and today the number of published papers with mathematical models becomes so large. In the 21st century, we can easily find different types of mathematical modeling even for the same/common problem: discrete/continuous time; stochastic/deterministic; non-spatial (e.g., with a certain mean-field approximation), semi-spatial (like the metapopulation dynamics model), or spatial (e.g., with a system of partial differential equations in continuous space, and a network or lattice-space in discrete space); non-structured (e.g., with a certain averaging over a heterogeneity) or structured (e.g., with the physiological state like age, sex, and epidemiological stage), etc. Further, there could be a mathematical modeling with different time scales embedded in a population dynamics, like first/slow process and time-delayed response. As a characteristic aspect of the modern development in the mathematical modeling for population dynamics, we may refer to the network-structured models for the structure of ecosystem or the spread of transmissible disease. Instead of such a rich development of the mathematical modeling for biological problems, as long as I know, the theoretical arguments specifically on mass extinction itself with such a mathematical modeling have been rarely done in mathematical biology (e.g., [18]).

Mass extinction can be characterized by its time scale in which a process makes a species disappear. A large spatial range of ecological disturbance which happens as a historic event may exterminate some species at the moment of its occurrence, like a natural calamity such as a volcanic explosion [4,27] or an asteroid collision [24]. Subsequently an environmental change induced by such a historic event may lead some survived species to their extinction [1,4,8,24,25], for example, due to their failure to adopt the new condition generated by such a change. Even though the environment could recover from such a momentous environmental perturbation in a certain period, some species extinctions could occur in a relatively short time scale before the environmental recovery [7,10,12,14,27].

On the other hand, a great environmental perturbation for the habitat by a natural calamity may induce a new interaction between different species which have no interaction before such a perturbation. Then the interspecific competition, prey-predator, or host-parasite relation could cause the extinction of a species [2,17,19]. Further the ecological interactions contained in the existing ecosystem may cause a knock-on effect to lead some species extinctions

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subsequent to a species extinction due to a natural calamity [9,16]. Such a species extinction would require in general a time scale of generations. It is the time scale in which the theory of ecological population dynamics has been particularly working.

The extinction of a wild species caused by a mutant spread in a population must follow a larger time scale in a large number of generations. An intraspecific competition is the essential dynamical factor to cause this kind of extinction. Although the population dynamics is certainly driven by such an intraspecific reaction within a population, the theory of evolutionary biology has rarely taken account of the dynamical process itself with an appropriate time scale. This is because the evolutionary biology holds the principal subject to understand the biological reason of the existence of a phenotype confirmed to exist in evolutionary history. Since the mutation and the emergence of a mutant are stochastic events, so is the extinction of a wild species due to a mutant species. Hence the fossil data can give just a partial information on the extinction of species in evolutionary history, and there could be many disappeared species which cannot be observed in the fossil data. Although some stochastic process models could give the estimation of the number of such missing species, we must recognize that such an estimation would necessarily depend on the hypothesis usually simplified in a mathematical sense.

Aside from theoretical/mathematical considerations on such missing species, the mathematical models have been used to argue the *kill mechanisms* which lead the population extinction for a variety of ecological situations [26]. Some of them were to consider the appropriateness of an existing biological hypothesis, and the other to generate a new biological hypothesis as a potential cue to understand a biological aspect of the population extinction. In the most general sense, the extinction of a species may be induced by different kill mechanisms together, furthermore with processes of different time scales. The mathematical modelings and the models have different mathematical characteristics for different time scales because of the difference in the kill mechanisms. They have been developed independently of each other in most cases, while we may now at the stage of their integration to re-approach the population dynamics for biological problems considered theoretically and mathematically in past.

It is the most reasonable way of thought that the arguments with the mathematical results obtained by the analysis on a mathematical model would be a theoretical reference to consider the biological problem, and must be combined with the existing biological knowledge about the problem [7,26]. This might seem little positive to take a research direction with mathematical modeling, while such a theoretical/mathematical reference could give an important or useful insight on the targeted biological problem, as seen in history of mathematical biology and related fields [3,13]. The consideration with a mathematical model could be called ‘virtual experiment’ [26] to propose such a theoretical/mathematical reference.

According to the species extinction, we must consider further the *kill mechanisms* under human impact in order to prevent the species extinction in future [5,6,11,15,20–22]. The time scale for such species extinction would be relatively short, but could be long in a number of generations. Even only from a viewpoint of species conservation, the mathematical modeling and the analysis on the mathematical model will be valuable to give a theoretical/mathematical reference, since we have the data and knowledge as far as we can obtain about the present and recent ecological system, while we do not have certainty about the future situation of ecological system around us [23]. Such theoretical/mathematical researches in conservation biology with respect to the species/population extinction could serve a future advance in the theory of mass action too.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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