Biological robustness and fragility

Robustness is considered to be a fundamental feature of complex evolvable systems [1]. It refers to the inherent ability of an organism or ecosystem to maintain specific functions or characteristics when exposed to specific perturbations. Specifically, the macroscopic biological phenomena associated with robustness may be classified into three areas: (i) adaptation, i.e., the ability to cope with changes in the external environment; (ii) a degree of insensitivity to the particular values of the parameters that describe the underlying microscopic processes; and (iii) slow degradation of a system's function following damage [2]. Robustness is found in a wide variety of biological examples. For example, organisms that are biologically robust are able to tolerate a wide range of environmental conditions, such as temperature fluctuations, changes in water availability, or exposure to pollutants. This allows them to survive and reproduce in a variety of different habitats, increasing their chances of survival. Similarly, ecosystems that are biologically robust are able to withstand disturbances, such as fire, drought, or disease outbreaks, and maintain their structure and function.

In contrast, biological fragility refers to the susceptibility of an organism or ecosystem to disturbances or changes in both internal and external, as well as natural and human-caused factors in its environment. For instance, environmental changes such as habitat fragmentation and lost resources as well as ecological properties such as food web structure, can introduce large disturbances that cause local extinctions. At this level, we can also define biological fragility as the degree of change in species abundances and in species composition, following disturbance. High rates of species turnover or population fluctuations characterize fragile ecosystems, and vice versa.

Numerous studies have demonstrated that the robustness and fragility of biological systems are interrelated [3]. An ecosystem that is highly stable over a period of several centuries, may be highly fragile in a short-term perspective [4]. Coniferous forests governed by frequent fire represent such an example. While the effects of the fire may seem catastrophic to the forest directly after the fire, they are not in the long term. Similarly, ecosystems that appear fragile at small scales may be stable when viewed at large spatial scales [5]. An interesting example is that many ecosystems governed by frequent fires may survive according to this principle.

Robustness is ubiquitous and essential. On the one hand, robustness contributes to evolvability. Complex biological systems must be robust to environmental and genetic perturbations in order to evolve, and often select for features that may enhance the robustness of the organism. In this case, maintaining satisfactory performance will determine the persistence and function of the organism [6]. On the other hand, numerous studies have shown that there is a positive correlation between robustness and species diversity [7], which is an important mechanism contributing to the origin of morphological complexity and species diversity (Figure 1). Organisms and ecosystems that are biologically robust are better able to tolerate a variety of environmental conditions, withstand disturbances, and maintain their structure and function. This increases their chances of survival and resilience to human impacts.

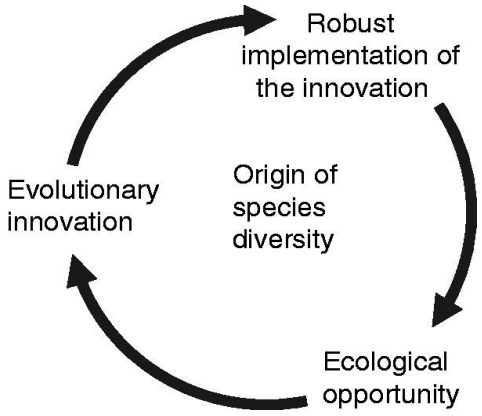

Figure 1: Proposed scenario as to how the interplay between evolutionary innovations, developmental robustness, and ecological opportunities contributes to the origin of species diversity.

Consequences of biological fragility can include decreased biodiversity, loss of critical ecosystem services, and increased vulnerability to disease or other disturbances. To avoid or reduce biological fragility, people could take steps to protect and conserve biodiversity, promote ecosystem resilience, and reduce human impacts on the environment. This can include practices such as sustainable land use, conservation of natural habitats, and reducing pollution. Additionally, monitoring and managing invasive species, and protecting endangered species can also help to reduce biological fragility [8]. It is important to note that the specific steps needed to avoid or reduce biological fragility will depend on the specific ecosystem and the causes of fragility.

References:

[1] Kitano, Hiroaki. "Biological robustness." Nature Reviews Genetics 5.11 (2004): 826-837.
[2] Félix M A, Barkoulas M. Pervasive robustness in biological systems[J]. Nature Reviews Genetics, 2015, 16(8): 483-496.
[3] Carlson J M, Doyle J. Complexity and robustness[J]. Proceedings of the national academy of sciences, 2002, 99(suppl_1): 2538-2545.
[4] Elliott M, Golub B. Networks and economic fragility[J]. Annual Review of Economics, 2022, 14: 665-696.
[5] Yi T M, Huang Y, Simon M I, et al. Robust perfect adaptation in bacterial chemotaxis through integral feedback control[J]. Proceedings of the National Academy of Sciences, 2000, 97(9): 4649-4653.
[6] Chaves M, Albert R, Sontag E D. Robustness and fragility of Boolean models for genetic regulatory networks[J]. Journal of theoretical biology, 2005, 235(3): 431-449.
[7] Melzer R, Theißen G. The significance of developmental robustness for species diversity[J]. Annals of Botany, 2016, 117(5): 725-732.
[8] Franco L M, Okray Z, Linneweber G A, et al. Reduced lateral inhibition impairs olfactory computations and behaviors in a Drosophila model of fragile X syndrome[J]. Current Biology, 2017, 27(8): 1111-1123.