JIS Journal of Interdisciplinary Sciences
Volume 8, Issue 1; 19-30
May, 2024. © The Author(s)
ISSN: 2594-3405

# Interdisciplinary Comments Highlighting the Importance of Supra-Microbiological Approaches to Covid-19 Pandemic

***Rodrigo Riera[1], [2]* Ada M. Herrera[3], Ricardo A. Rodríguez[4]***

***[1]Biodiversity and Conservation Group, University of Las Palmas de Gran Canaria, Spain***
***[2]Department of Ecology, Catholic University of the Most Holy Conception, Chile***
***[3]Association for the Interdisciplinary Advance in Basic and Applied Sciences, Spain***
***[4]Independent Researcher, Spain***
***rodrigo.riera@ulpgc.es***

**Abstract**: *This article explores the links between the Covid-19 pandemic and the principles of biology using applied physics as a common analytical framework. Such links involve supra-microbiological questions: (i) Does the interaction humans ↔ pandemics fit the mainstream of evolutionary biology? (ii) Why does there appear to be an increase in pandemic frequency? (iii) Why are these pandemics preferentially emerging in the Far East? (iv) Why do the populations of zones that belong to the same economic system react differently to the same pandemics? v) Are there reasons to expect these outbreaks to become more frequent? Methodologically speaking, this article is simple: interdisciplinary links are established and statistical procedures based on data extracted from international institutions are interspersed in order to support the respective interdisciplinary link. The results suggest that (a) zoonotic diseases do not coincide with what is expected according to the orthodox Darwinian approach on at least two points (gradualism, and evolutionary process at the population scale); (b) socioeconomic niches and socio-diversity (the social equivalent of biodiversity) connected to them act as strong selective pressures either for or against pandemics; (c) socioeconomic development is equivalent to a drift from r to K in human systems, and as a result there is a drift from K to r in ecosystems, which favors a tendency to increase pandemic frequency; (d) eco-historical analysis indicates that those countries or areas that display a faster rate of economic growth act as socio-economic Maxwell's demons that modulate, either voluntarily or involuntarily, the emergence of pandemics.*

**Keywords**: Anthropocene, evolutionary biology, information, pandemic outbreaks, species diversity, socioeconomic development, r/K selection theory

## Introduction

*Humans, pandemics, and conventional evolutionary theory*

The sudden zoonotic contact between humans and Covid-19 seems to be a jump of SARS-

CoV-2 that challenges Darwinian gradualism. In Covid-19, bats appear to be the reservoir of SARS-CoV-2 virus (Zhou et al., 2020). One of the key premises of Darwinism is the colonization of novel ecological niches. The conquest of a new host population by a parasite is ecologically coherent with the aforementioned premise. However, according to Darwin and the mainstream of evolutionary thinking, this conquest must be *gradual, extremely slow,* but this has not been the case with SARS-CoV-2 virus. Besides, the conventional view to assess if a given life form has evolved toward a new niche is based on anatomical criteria, or their molecular equivalents in this case, rather than on biological energy criteria (trophodynamics).

SARS-CoV-2 virus has relatively few biochemical changes reflected in its molecular structure, but it shifted from the available somatic energy of a small vertebrate on a local geographic scale, to the somatic and exosomatic energy of a large rational vertebrate, underpinning a global invasion. Therefore, small molecular changes that could be considered consistent with Darwinian gradualism have promoted a drastic ecological change towards a different adaptive zone millions of times wider, in full coherence with what is expected according to the organic biophysics of ecosystem (OBEC, see the first comments on this term in Rodríguez et al., 2017a; a summary of several OBEC models is provided by Rodríguez et al., 2019).

It is well known that several species can be simultaneously involved in the evolutionary jumps of pathogens, e.g. the Spanish flu (Oxford et al., 2005), A (H1N1) swine influenza (Butler, 2009) or SARS (Hu et al., 2017). Congruently, from the functional point of view which is the analytical axis of ecology, the response of human beings to the attack of SARS-CoV-2 virus is not at the population level but at the ecosystem level. In other words, if species diversity ($H_b$ or biodiversity) is the most encompassing indicator of development and conservation level in natural ecosystems; sociodiversity ($H_s$, following the original proposal by Shannon, 1948); it is the best indicator of human development (see Rodríguez & González, 2000; and Rodríguez & Cáceres-Hernández, 2018).

$$H_s = -\sum_{i=1}^{\psi}\left(\frac{n_i}{N}\cdot ln\frac{n_i}{N}\right)$$

Where $\psi$ is the total number of occupations or socioeconomic niches in the human population analyzed; $n_i$ is the number of individuals of socioeconomic niche $i$; and $N = \sum_{i=1}^{\psi} n_i$. For example, $\psi$ = 796; and $\sum_{i=1}^{\psi} n_i$= 315,826,172.00 individuals in Supplementary Table 1 (ST1; data from: Bureau of Labor Statistics, Occupational Employment Statistics: https://www.bls.gov/oes/tables.htm. Department of Defense Manpower Data Center: https://www.dmdc.osd.mil/appj/dwp/dwp_reports.jsp).

Thus, which taxonomic group has granted the species diversity and energy to produce Covid-19 pandemic? Bats? Viruses? Humans? Or all of them? This latter condition seems the most plausible, as well as the one that leads us to prioritize an ecosystem-based rather than a population-based evolutionary context. Hence, evolutionary processes of human pathogens do not take place at the population level, as it was postulated by Darwin (1859), but at the level of ***socioeconomic ecosystems***; and all the concurrent natural species as well as socioeconomic niches in the city context (see the introduction of this concept by Rodríguez & Cáceres-Hernández, 2018) exert combined selection pressures by evolving together.

In this regard, some evolutionary traits linked to the quantum-like traits of ecosystem dynamics have remained hidden until recent findings from the OBEC (Rodríguez et al., 2015). These traits indicate toward the deployment of sudden leap-like trophodynamic changes, instead of in favor of gradualism, because every ecological assemblage or taxocene has a typical value of a constant named as $h_e^{ec}$ or "ecological equivalent of the Planck's constant" in physics, where $h$ = 6.62607015E−34 J·Hz$^{-1}$. In the ecological context, $h_e^{ec}$ = 6.62607015E±$\varphi$ $J_e$·nat/individual, where $\varphi = -x_i, \ldots, -3, -2, -1, 0, +1, +2, +3, \ldots, +x_i$ depending on the type of taxocene explored. Thus, $h_e^{ec}$ indicates the minimum amount of exchange of eco-kinetic energy ($E_e$) allowed per individual in function of species diversity ($H_b$) oscillations with a wavelength ($\lambda_e$) of $x$ nat/individual. $E_e$ (see equation below, according to Rodríguez et al. 2012, 2013) can be successfully used as an operative proxy of trophic energy expressed in eco-Joule −$J_e$−, in a similar way in which kinetic energy in Newtonian mechanics is $E = ½m \times v^2$ (Halliday et al., 2011) and it is expressed in Joule (J).

$$E_e = ½(m_p \cdot I_e^2)$$

Where $m_p$ is mean biomass (body weight) per individual per plot; and $I_e$ is an ecological indicator of the intensity of dispersal activity with similar statistical traits to those of physical velocity (for details, Rodríguez et al. 2013). That is to say, any fluctuation of $H_b$ is limited by a minimum of $E_e = h_e^{ec}$. The value of $h_e^{ec}$ decreases with the decrease of mean body weight per individual. The lower the value of $h_e^{ec}$ the more probable the change in $H_b$, and the higher the frequency of evolutionary jumps. This seems to be especially true in pathogens like SARS-CoV-2 which, due to their very small size, should have a very low value of $h_e^{ec}$ that can be reached and disturbed in an easier way in comparison with higher body weight organisms. The exact value of $h_e^{ec}$ for viruses is unknown so far, but it should be at least significantly lower than $h_e^{ec}$ = 6.62607015E−13 $J_e$·nat/individual; a value measured for brackish water microscopic algae by Rodríguez et al. (2013).

If energy in ecosystems can only be exchanged in discrete packages ($h_e^{ec}$), and speciation means the permutation of niches supported by changes between energy levels, then the most direct conclusion is that gradualism does not match with the interdisciplinary analysis of evolutionary processes. Genetic changes could be as gradual as Darwinism postulates. Nevertheless, if the selective pressures have a discrete character because of the existence of $h_e^{ec}$, then the effects of genetic gradual changes will not manifest until they become equivalent, at the phenotypic level, to ecological changes proportional to an integer multiple of $h_e^{ec}$. In other words, the phenotypic expression of genetic gradualism is *sieved* by the discontinuity or granularity of the trophodynamic environment. This is consistent with all the premises of Darwinism included in the extended evolutionary synthesis (Pigliucci & Finkelman, 2014), but with the requirement that gradualism should be "sacrificed" in order to make the theory coherent with reality due to the influence of new ecological findings that are not included in those cited by Laland et al., (2015) in favor of saltation.

In summary, it is logical that the paradigm of each science should be modified as other sciences provide new collateral evidence, although it is well known that the standard trend of paradigms is to maintain the permanence of the *status quo* beyond what is convenient (Riera et al., 2018). As a result, the dynamics of pandemics does not entirely agree with two of the key principles of conventional evolutionary theory. Besides, it is not fruitful to achieve a reliable connection between evolutionary theory and ecology without a dependable understanding of ecosystem dynamics (Rodríguez et al. 2017b) which has been regarded as urgent (Huneman & Walsh, 2017).

**Is Covid-19 a mere contingency, or a warning call from nature?**

Regardless the constancy of temperature at the macroscopic scale under equilibrium in a given mass of enclosed gas, there is a spectrum of molecular velocity values at the microscopic scale. Taking into account the above-described circumstance, Maxwell (1872) proposed a *gedankenexperiment* based on the hypothetical existence of a Maxwell Demon (MD) who could evade the fulfillment of the second law of thermodynamics by simple selection. That is, separating the fastest from the slowest molecules isolated from each other by an adiabatic septum to obtain a gradient able to produce work. However, the second law of thermodynamics is the most reliable law of nature so far (Eddington, 1930; Rifkin & Howard, 1980). Therefore, when MD came onto the scene, some researchers (Smoluchowski, 1912; Szilard, 1929; Bennett, 1987) developed objections to the existence of the MD in the real world. We herein focus on the relationship between Smoluchowski's objection and the Covid-19 pandemic.

A key point is highlighting the statement of O'Neill and Kahn (2000), since they comment about a noteworthy functional and structural compartmentalization of the planet whose emergence has coincided with the worsening of environmental crisis. This is a first clue to believe that we are inefficient as MDs. Smoluchowski's objection states that the MD is not an external observer, but belongs to the system itself, and this interferes with its task as an efficient selector of molecules: literally, the M.D. can't help but get hit by some molecules from time to time. Smoluchowski's objection, in the interdisciplinary realm of science, means that the anthropogenic influences on the natural environment also destabilize socio-economic systems themselves by rebounding as a result of the effects of complex environmental interactions. This effect causes *uncertainty*, i.e., *entropy*, in human decisions and obstructs the effectiveness of our actions of regulation on the biosphere. This section, seen with skepticism and isolated from collateral evidence would seem to be based on a sort of metaphor. However, we should take into account the increasing importance of applied physics to understand ecological issues (Gouveia et al., 2020), including the OBEC, which has produced a set of non-contingent and empirically tested models that allows the interpretation of key issues of ecosystem functioning in full agreement with the principles and equations of conventional physics (Herrera et al., 2023), in opposition to other approaches detached from physics (see a debate about this topic in Riera et al., 2024).

The main traits of a socioeconomic MD that deserve attention on the part of any interdisciplinary approach to pandemics are the following: *i*) It should be placed approximately in the middle of a gradient of … something, in order to perform its regulatory action by keeping and increasing gradients between two or more social compartments. *ii*) It should be the preferential target of pandemics, because of two main reasons: *ii.a*) its regulatory action implies the intense contact with many "social molecules" (individuals that perform different socioeconomic niches); *ii.b*) its regulatory action needs to accumulate large amounts of energy, and this condition is sought to take advantage by human pathogens. *iii*) Starting from item (*ii*), either at the international or national level, a socioeconomic MD should not be located in the richest areas of social ecosystems, but in those areas where the rate of economic growth is more intense.

According to traits (*ii.a*) and (*iii*), it is foreseeable that the highest probability of epidemic emergence at the international scale should be associated with China, because it has had the fastest mean annual growth of GDP per capita (10.812%, see cell B13 in ST2) during the last 20 years worldwide. Hence, China is the most active socioeconomic MD nowadays because its business system, including companies specialized in R+D+I linked to biotechnology and working with microbes, are taking advantages from the international gradient mainly in an indirect way via their close links with the USA economy. In addition, there are internal gradients between the richest provinces of the Pacific coast of China and the poorest provinces of deep China (see cell E25 in ST2). The inevitability of gradients driven by social MDs with a deep impact on nature as a result of performing a given amount of net economic work for getting wealth is in agreement with the opinion of Blaug (1997), about the unbalanced nature of economic growth everywhere and every time. After all, it is not the first time that a widely lethal pandemic has been associated with one of the countries with the highest economic growth in a given historical period. For example, the first documented cases of the misnamed Spanish Flu were recorded in the United States of America (Barry, 2004; Mata, 2017; Spinney, 2018), the country that, in 1918, had the highest association between GDP and GDP per capita all over the world (href 1). In antiquity, widespread outbreaks of lethal pandemics also occurred during the sequence of contraction and expansion of the Roman Empire (e.g., see Meier, 2016; Duncan-Jones, 2018; Zonneveld et al., 2024).

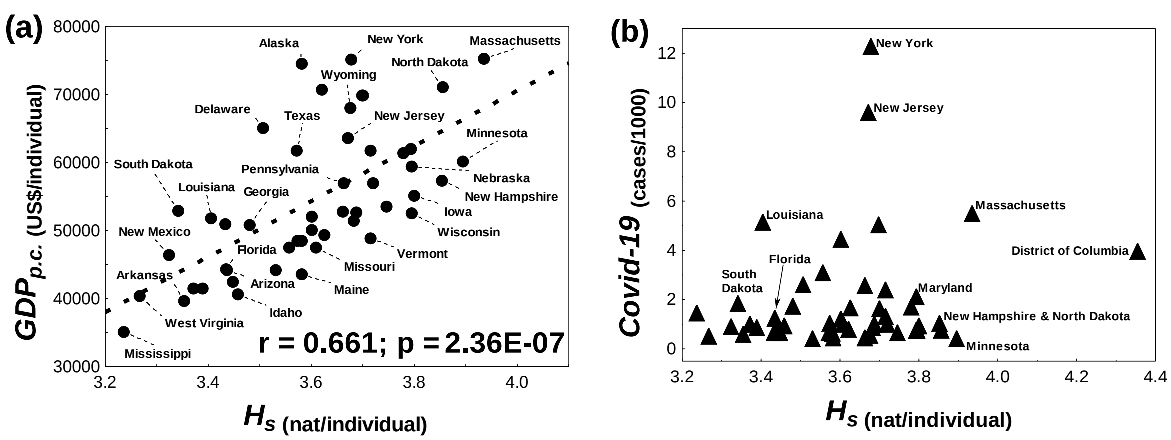
About traits (*i*) and (*ii.b*), they should be regarded as the gradient of sociodiversity values ($H_s$, see the first section of this article). This assumption implies the need to empirically test whether $H_s$ is correlated with a relevant indicator of wealth routinely used in economics. According to Fig. 1a, there is a correlation between $H_s$ and GDP per capita for mainland U.S. states (the U.S. Bureau of Economic Statistics, 2020) of $r = 0.661$, $p = 2.359\text{E-}07$; with $N = 49$ excluding the outlier effect of the District of Columbia. Its inclusion ($N = 50$) would raise the correlation to $r = 0.745$, $p = 5.44\text{E-}10$. Therefore, $H_s$ can be used to explore the plausibility of item (*i*), with the advantage that $H_s$ does not have the well-known drawback of GDP per capita in regard to the possibility of yielding equal values in spite of contrasting distributions of income (i.e., standard deviation effect; e.g.: [$100 + $1 + $1]/3 = $34, and

[$34 + $34 + $34]/3 = 34 too, despite the fact that the effect of the actual degree of income disparity is very different between the two cases). Due to the aforementioned correlation, in those cases where raw socioeconomic data to calculate $H_s$ are not available, then it is possible to replace $H_s$ by GDP per capita.

According to the resulting hypothesis starting from the combination of traits (*i*) and (*ii*), it is expected that the scatterplot $H_s$ vs. the total number of confirmed cases of Covid-19 per 1000 inhabitants (variable *Covid-19*) per USA state (Johns Hopkins University of Medicine. Coronavirus Resource Center, 2020) should show a unimodal pattern similar to an inverted V (see Fig. 1b), in agreement with a similar shape of the scatterplot of $H_s$ vs. total socio-kinetic energy ($E_{sT}$) per state (see Figs. 1b and 1c). The scatterplot $H_s$, *Covid-19/*$_{1000}$ and the scatterplot $H_s$, $E_{sT}$ have a similar shape, just as it is theoretically expected according to our premises from OBEC reflected in traits (*i*) and (*ii.b*), see above.

$$E_{sT} = N \cdot E_s = N \cdot \left(\frac{m_s \cdot I_s^2}{2}\right)$$

where $E_{sT}$, given the above-mentioned functional equivalence between natural ecosystems and cities, is calculated by extending the methods of Rodríguez et al. (2012; 2013) to the econophysical approach proposed by Rodríguez & Cáceres-Hernández (2018); $m_s$ is the mean income per individual per socio-economic plot, or GDP per capita; $I_s$ is an indicator of the intensity of dispersal activity of individuals across a particular socioeconomic structure deployed in a given geographic space, with similar statistical traits to those of physical velocity; and $N$ is the total number of individuals in the sample ($E_{sT}$ is the extensive expression of $E_e$, but in society). Is it plausible to assume that the unimodal distribution between *Covid-19* and $H_s$ observed in Fig. 1b is a typical pattern? Figures. 1d, 1e, 1f, and 1g are in favor of an affirmative response to this question.



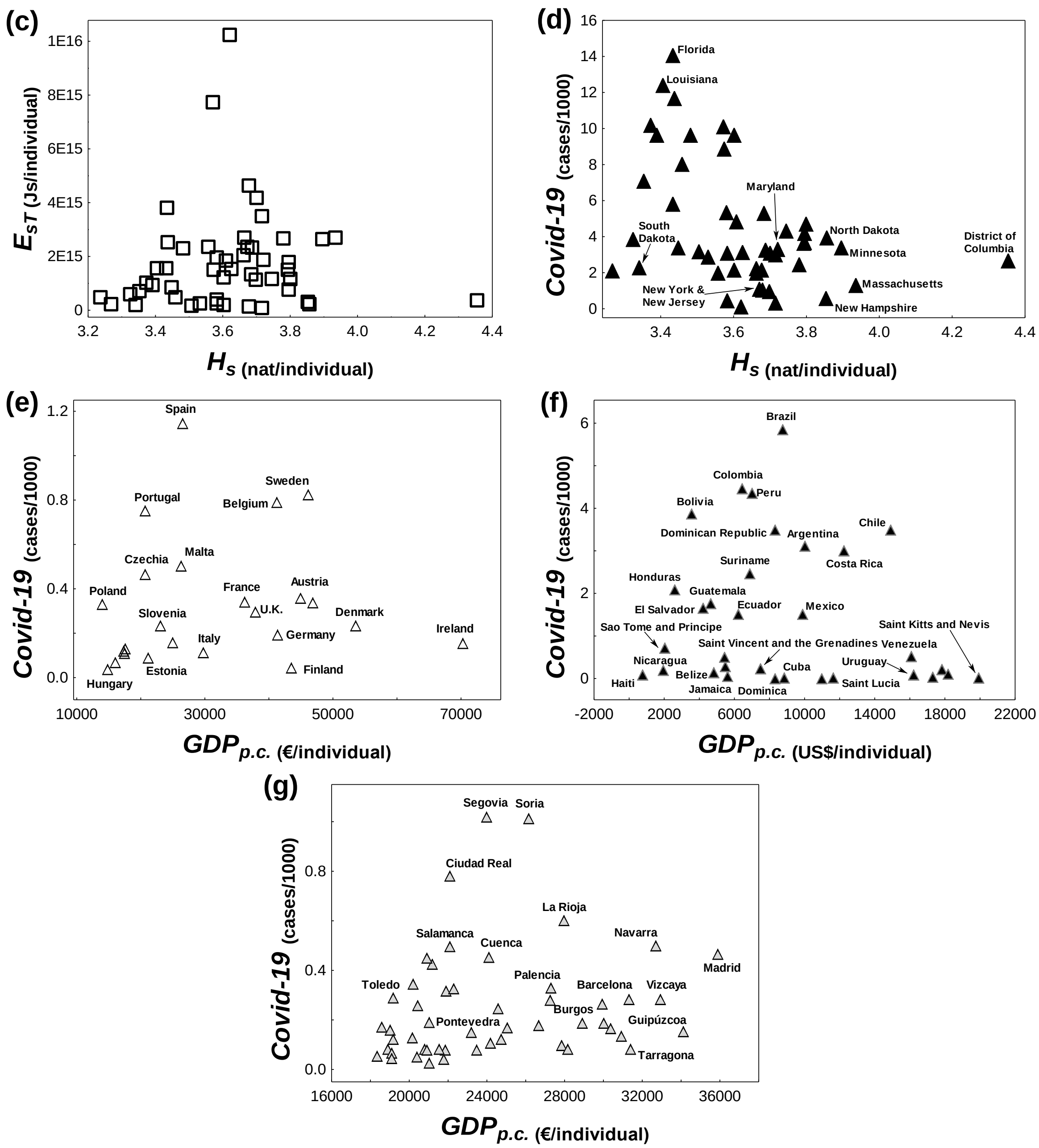



Figure 1. Relationship between Covid-19 and OBEC indicators applied to human ecosystems.
Note: **(a)** Correlation between sociodiversity ($H_s$) and Gross Domestic Product per capita ($GDP_{p.c.}$) per USA state. **(b)** Relationship between $H_s$ and the number of cases of Covid-19 per 1000 inhabitants per USA state accumulated from January 21 to April 18, 2020 (*Covid-19*). **(c)** Relationship between $H_s$ and total socio-kinetic energy ($E_{sT}$) per USA state. **(d)** The equivalent to Fig. 1b from July 3 to August 3, 2020. **(e)** Relationship between $GDP_{p.c.}$ and the number of cases of Covid-19 per 1000 inhabitants

per European Union country accumulated from July 3 to August 3, 2020 (data from: Johns Hopkins University of Medicine. Coronavirus Resource Center, World Bank. **(f)** The equivalent to Fig. 1e for Latin American and the Caribbean countries accumulated from July 3 to August 3, 2020 (data in ST3). **(g)** The equivalent to Fig. 1e for Spain provinces on March 20, 2020 (data from: Original data of GDPp.c. in 2017 according to the Instituto Nacional de Estadística of Spain (INE). All these calculations and charts were performed by means of StatSoft Inc. (2014).

**Large-scale ecological forecasting of deadly outbreak trends**

The parallelism between the above-described Maxwellian *gedankenexperiment* and the respective existence of *r*-strategists (species with high reproductive and dispersal capability; e.g., at the scale of the human species, –given the fulfillment of *r*/*K* selection theory at the human population level as well, see Rushton, 1988; Silverman, 1990; Fog, 1997; Alfonso-Sánchez et al., 2003– all population groups near the bottom left corner of all panels in Fig. 1) and *K*-strategists (just the opposite to *r*-strategists according to Reznick, et al. 2002; e.g., at the scale of the human species, all population groups near the upper right corner of panel (a) and the lower right corner of all other panels in Fig. 1) in natural ecosystems is obvious.

The key point is that *r* and *K* species do not receive the same treatment on the part of *Homo sapiens sapiens* in his behavior as MD. Rusticity + adaptability to a wide variety of environments + short life cycle + abundant offspring + rapid ontogenetic growth + high dispersal capability + tolerance to overcrowding is an ideal combination of traits for breeding a given species with economic aims. Thus, almost all the species whose existence is preferably subsidized by humans with economic goals are *r*-strategists. Besides, given the limited amount of available solar power at the planetary scale, the above-mentioned subsidy means that the loss of biodiversity is not arbitrary, but unwittingly selective: it favors *r*-strategist species with low $h_e^{ec}$ values and simultaneously reduces the prevalence of *K*-strategist species with high $h_e^{ec}$ values.

This means that we are peeling away eco-evolutionary layers of *K*-strategist species, getting closer and closer to species linked to the center of the "eco-evolutionary onion" of the biosphere, where there is a plethora of potential pathogens with very low $h_e^{ec}$ values (as the SARS-CoV-2), waiting for an opportunity to evolve at the expense of the human population living in socioeconomic ecosystems. This means that, if the global decline of species diversity follows the same current course, pandemics (either those that directly affect humans or those that attack the crops and livestock that feed us) will become more and more frequent in the future. It is as if to the same extent that the scatterplots in Fig 1 are preferentially shifted to the right (higher socioeconomic development, i.e.; social *K*-like), the natural species are shifted to the left (natural *r*) in their respective ecosystems. This risk increases with the current thawing of permafrost, a paleo-reservoir of countless *r*-strategist species, many of which are potentially pathogenic (Christie, 2021; Yarzábal et al., 2021; Wu et al., 2022).

In summary, we have tried to show that the problem of pandemics must also be analyzed from a macroscopic point of view, linking several fields of science in a simple and integrative way. Despite the current level of advance of science and technology, there is always an ocean of ignorance in front of us, and we need to avoid losing our capability to be surprised by the infinite potentiality for eco-evolutionary innovation that nature displays in response to our influence on it. In such a sense, the SARS-CoV-2, besides an overwhelming humanitarian catastrophe, should also be seen as a lesson by means of ecology for humankind as a whole.

***Acknowledgments***

We would especially like to acknowledge the attention to detail, analytical skills, and accuracy of the appropriate advice provided by the reviewers of the original manuscript.

**Declaration of conflicting Interests**

No potential conflict of interest.

**Funding**

This manuscript was developed from the authors' personal resources; no ad hoc funding was involved in its preparation.

**References**

Alfonso-Sánchez, M.A., Peña, J.A., & Calderón, R. (2003). Time trends and determinants of completed family size in a rural community from the Basque area of Spain (1800-1969). *Journal of Biosocial Science*, *35*(4), 481–497. https://doi.org/10.1017/s002193200300587x.

Barry, J.M. (2004). The site of origin of the 1918 influenza pandemic and its public health implications. *Journal of Translational Medicine*, *2*(1), 3. https://doi.org/10.1186/1479-5876-2-3

Bennett, C.H. (1987). Demons, engines and the second law. *Scientific American*, *257*(5), 108–116. https://doi.org/10.1038/scientificamerican1187-108

Blaug, M. (1997). The Methodology of Economics. Or How Economists Explain. Cambridge University Press, New York.

Butler, D. (2009). How severe will the flu outbreak be? Nature, 459(7243), 1−15. https://doi.org/10.1038/459014a

Christie, A. (2021). Blast from the Past: Pathogen Release from Thawing Permafrost could lead to Future Pandemics. *Cambridge Journal of Science & Policy*, *2*(2), 1–8. https://doi.org/10.17863/CAM.74501

Darwin, C. (1859). *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life.* John Murray, London.

Duncan-Jones, R. (2018). The Antonine Plague Revisited. *ARCTOS: Acta Philologica Fennica*, *52*, 41–72.

Eddington, A.S. (1930). *The Nature of the Physical World.* Macmillan, New York.

Fog, A. (1997). Cultural *r/K* Selection. *Journal of Memetics - Evolutionary Models of Information Transmission*, *1*(1), 14–28. http://jom-emit.cfpm.org/1997/vol1/fog_a.html.

Gouveia, S.F., Rubalcaba, J.G., Soukhovolsky, V., et al. (2020). Ecophysics reload—exploring applications of theoretical physics in macroecology. *Ecological Modelling, 424*, 109032. https://doi.org/10.1016/j.ecolmodel.2020.109032

Halliday, D., Resnick, R., & Walker, J. (2011). *Fundamentals of Physics.* John Wiley & Sons, Inc., New Jersey.

Herrera, A.M., Riera, R., & Rodríguez, R.A. (2023). Alpha species diversity measured by Shannon's *H*-index: Some misunderstandings and underexplored traits, and its key role in exploring the trophodynamic stability of dynamic multiscapes. *Ecological Indicators, 156*, 111118. https://doi.org/10.1016/j.ecolind.2023.111118

Href 1 https://ourworldindata.org/grapher/total-gdp-vs-gdp-per-capita-maddison?time=1..1935

Hu, B., Zeng, L.P., Yang, X.L., et al. (2017). Discovery of a rich gene pool of bat SARS-related coronaviruses provides new insights into the origin of SARS coronavirus. *PLOS Pathogens, 13*(11), e1006698. https://doi.org/10.1371/journal.ppat.1006698

Huneman, P., & Walsh, D.M. (Eds.) (2017). *Challenging the Modern Synthesis: Adaptation, Development, and Inheritance.* Oxford University Press, New York.

Laland, K.N., Uller, T., Feldman, M.W., et al. (2015). The extended evolutionary synthesis: its structure, assumptions and predictions. *Proceedings of the Royal Society B: Biological Sciences, 282*(1813), 20151019. https://doi.org/10.1098/rspb.2015.1019

Mata, S. (2017). *Cómo el Ejército Americano Contagió al Mundo la Gripe Española*. Ediciones Amanecer, Madrid.

Maxwell, J.M. (1872). *Theory of Heat.* Longmans, Green, & Co., London.

Meier, M. (2016) The 'Justinianic Plague': the economic consequences of the pandemic in the eastern Roman empire and its cultural and religious effects. *Early Medieval Europe*, *24*, 267–292. https://doi.org/10.1111/emed.12152

O'Neill, R.V., & Kahn, J.R. (2000). *Homo economicus* as a keystone species. *BioScience, 50*(4), 333–337. https://doi.org/10.1641/0006-3568(2000)050[0333:HEAAKS]2.3.CO;2

Oxford J.S., Lambkin, R., Sefton, A., et al. (2005). A hypothesis: The conjunction of soldiers, gas, pigs, ducks, geeses, and horses in northern France during the Great War provided the conditions for the emergence of the "Spanish" influenza pandemic of 1918–1919. *Vaccine, 23*(7), 940–945. https://doi.org/10.1016/j.vaccine.2004.06.35

Pigliucci, M., & Finkelman, L. (2014). The extended (evolutionary) synthesis debate: where science meets philosophy. *BioScience, 64*(6), 511–516. https://doi.org/10.1093/biosci/biu062

Reznick, D., Bryant, M.J., & Bashey, F. (2002). *r*- and *K*-selection revisited: the role of population regulation in life-history evolution. *Ecology, 83*(6), 1509–1520. https://doi.org/10.1890/0012-9658(2002)083[1509:RAKSRT]2.0.CO;2

Riera, R., Rodríguez, R.A. Herrera, A.M., et al. (2018). Endorheic currents in ecology: an example of the effects from scientific specialization and interdisciplinary isolation. *Interdisciplinary Science Review, 43*(2), 175−191. https://doi.org/10.1080/03080188.2017.1371480

Riera, R., Fath, B.D., Herrera, A.M., & Rodríguez, R.A. (2024). A strategic roadmap for interdisciplinary modeling in ecology: The result of reading 'Defining an ecological equation of state: Response to Riera et al. 2023′ (Newman et al., 2023). *Ecological Modelling, 490*, 110658. https://doi.org/10.1016/j.ecolmodel.2024.110658.

Rifkin. J., & Howard, T. (1980). *Entropy, a New World View*. Viking Press, New York.

Rodríguez, R.A., & González, I. (2000). La diversidad socioeconómica como medida de desarrollo humano [Socioeconomic diversity as a measure of human development] *Investigación y Economía, 60*, 13–33.

Rodríguez R.A., Herrera, A.M., Otto, R., et al. (2012). Ecological state equation. *Ecological Modelling, 224*(1), 18–24. https://doi.org/10.1016/j.ecolmodel.2011.10.020

Rodríguez, R.A., Herrera, A.M., Delgado, J.D., et al. (2013). Biomass-dispersal trade-off and the functional meaning of species diversity. *Ecological Modelling, 261/262*, 8–18. https://doi.org/10.1016/j.ecolmodel.2013.03.023

Rodríguez, R.A., Herrera, A.M., Riera, R., et al. (2015). Distribution of species diversity values: a link between classical and quantum mechanics in ecology. *Ecological Modelling, 313*, 162–180. https://doi.org/10.1016/j.ecolmodel.2015.06.021

Rodríguez, R.A., Duncan, J.M., Delgado, J.D., et al. (2017a) Assessment of ecosystem trophodynamic power: A model based on the power equation for an oscillating string. *Ecological Modelling, 362*, 80–86. http://dx.doi.org/10.1016/j.ecolmodel.2017.08.019.

Rodríguez, R.A., Duncan, J.M., Vanni, M.J., et al. (2017b). Exploring the analytical consequences of ecological subjects unwittingly neglected by the mainstream of evolutionary thought. *Ecological Modelling, 355*, 70−83. http://dx.doi.org/10.1016/j.ecolmodel.2017.03.029

Rodríguez, R.A., & Cáceres-Hernández, J.J. (2018). Information, entropy, value, and price formation: An econophysical perspective. *Physica A*: *Statistical Mechanics and Applications, 512*, 74−85. https://doi.org/10.1016/j.physa.2018.08.005

Rodríguez, R.A., Riera, R., Herrera, A.M., et al. (2019). Degrees of freedom: Definitions and their minimum and most meaningful combination for the modelling of ecosystem dynamics with the help of physical principles. *Ecological Modelling, 392*, 226–235. https://doi.org/10.1016/j.ecolmodel.2018.11.021

Rushton, J.P. (1988). Do *r/K* reproductive strategies apply to human differences? *Social Biology*, *35*(3/4), 337–40. https://doi.org/10.1080/19485565.1988.9988712

Shannon, C.E. (1948). A mathematical theory of communication. *The Bell System Technical Journal, 27*(3), 379–423, 623−656. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x

Silverman, I. (1990). The *r/K* theory of human individual differences: Scientific and social issues. *Ethology and Sociobiology, 11*(1), 1–9. https://doi.org/10.1016/0162-3095(90)90002-N

Smoluchowski M. (1912) Experimentell nachweisbare, der üblichten Thermodynamik widersprechende Molekularphänomene [Experimentally detectable molecular phenomena that contradict the usual thermodynamics]. *Physikalische Zeitschrift, 13*, 1069–1080. http://eudml.org/doc/215787

Spinney, L. (2018). *Pale Rider: The Spanish Flu of 1918 and how it Changed the World*. Vintage, London. p. 36.

StatSoft, Inc. (2014). *STATISTICA* (data analysis software system), version 12. www.statsoft.com.

Szilard, L. (1929). Über die Entropieverminderung in einem thermodynamischen System bei Eingriffen intelligenter Wesen [About entropy reduction in a thermodynamic system during interventions by intelligent beings]. *Zeitschrift für Physik*, *53*, 840–856. https://doi.org/10.1007/BF01341281

Wu, R., Trubl, G., Taş, N., et al. (2022). Permafrost as a potential pathogen reservoir. *One Earth, 5*, 351–360. https://doi.org/10.1016/j.oneear.2022.03.010

Zhou P, Yang X, Wang X, et al. (2020). A pneumonia outbreak associated with a new coronavirus of probable bat origin. *Nature, 579*, 270–273. https://doi.org/10.1038/s41586-020-2012-7

Yarzábal, L.A., Salazar, L.M.B. & Batista-García, R.A. (2021). Climate change, melting cryosphere and frozen pathogens: Should we worry…?. *Environmental Sustainability*, *4*, 489–501. https://doi.org/10.1007/s42398-021-00184-8

Zonneveld, K.A.F., et al. (2024). Climate change, society, and pandemic disease in Roman Italy between 200 BCE and 600 CE. *Science Advances, 10*, eadk1033. https://doi.org/10.1126/sciadv.adk1033

**Paper Received April 25, 2023; Accepted February 16, 2024; Published May 2, 2024**