



Contents lists available at ScienceDirect

Science of the Total Environment

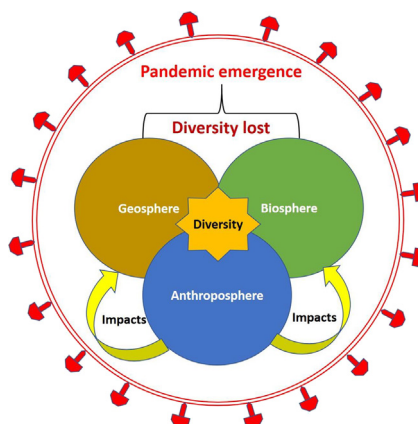
journal homepage: www.elsevier.com/locate/scitotenv

Diversity lost: COVID-19 as a phenomenon of the total environment

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GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 10 August 2020

Received in revised form 12 November 2020

Accepted 15 November 2020

Available online xxxx

Editor: Damia Barcelo

ABSTRACT

If we want to learn how to deal with the COVID-19 pandemic, we have to embrace the complexity of this global phenomenon and capture interdependencies across scales and contexts. Yet, we still lack systematic approaches that we can use to deal holistically with the pandemic and its effects. In this Discussion, we first introduce a framework that highlights the systemic nature of the COVID-19 pandemic from the perspective of the total environment as a self-regulating and evolving system comprising of three spheres, the Geosphere, the Biosphere, and the Anthroposphere. Then, we use this framework to explore and organize information from the rapidly growing

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Keywords:

Pandemics
Complexity
Interdisciplinary
Total environment
COVID-19

number of scientific papers, preprints, preliminary scientific reports, and journalistic pieces that give insights into the pandemic crisis. With this work, we point out that the pandemic should be understood as the result of preconditions that led to depletion of human, biological, and geochemical diversity as well as of feedback that differentially impacted the three spheres. We contend that protecting and promoting diversity, is necessary to contribute to more effective decision-making processes and policy interventions to face the current and future pandemics.

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1. Introduction

Earth has been considered a symbiotic, self-regulating system sustained by complex interactions between non-living (the Geosphere) and living (the Biosphere and Anthroposphere) systems (Lovelock and Margulis, 1996; Cazzolla, 2017; Cazzolla Gatti, 2018). The overexploitation of Biosphere's and Geosphere's diversity by human societies has led to the emergence of dangerous animal-borne contagions (causing zoonoses), such as human immunodeficiency viruses (HIV), simian foamy viruses (SFV), rabies, malaria, dengue fever, meningitis, among others (Brooks et al., 2019). Centuries of abusive expansionism by human activities has threatened geochemical, biological, and human diversity, which recently resulted, among others, in the pandemic caused by SARS-CoV-2 (Cazzolla Gatti, 2020a). Pandemic events have made it increasingly clear that our societies - characterized by growing globalization, urbanization, industrial livestock breeding, unsustainable agricultural intensification, and natural resources exploitation - disrupt Earth's symbiotic, self-regulating system, lead to a loss of diversity, and create the conditions for new pandemics to arise (Brooks et al., 2019; Gibb et al., 2020; UNEP, 2020). New potential pandemics (other than COVID-19) are already on the horizon (Sun et al., 2020a, 2020b).

The COVID-19 pandemic has brought science back into the foreground of the public discourse about the future of our planet. Epidemiologists, virologists, and other health scientists have greatly contributed to our understanding of the pandemic as a global health phenomenon (Acter et al., 2020). Furthermore, there is increasing awareness that the COVID-19 pandemic is neither exclusively, nor primarily, confined to the health domain and that we need to address it as linked to the broader environmental and societal crisis of a global society that is dangerously overexploiting planetary resources (Steffen et al., 2015). However, the current fragmentation of research approaches risks to provide us only with limited and short-sighted perspectives on this complex and global phenomenon. To date, we still lack the analytical tools and frameworks that can help to improve interdisciplinary approaches that capture the complexity of the phenomenon that we are dealing with. This, in turn, limits the capacity of scientific research to contribute insights that can inform policy and interventions to address the COVID-19 pandemic.

This discussion paper contributes to ongoing debates about the current pandemic crisis in two main ways. First, we present an intuitive framework to analyze the COVID-19 pandemic as a phenomenon that emerges from and affects the whole total environment, as a complex evolving system composed of interdependent spheres: Geosphere, Biosphere, and Anthroposphere (SciTotEn, 2020). Our framework provides an analytical tool to organize insights about geological, biological, and human diversity in relation to the many interdependencies characterizing the current pandemic. By diversity we refer here to the fundamental and emergent characteristic of life, as life tends to evolve towards diversity, diversity to stability, and stability to maintaining the conditions that guarantee the emergence of life (Cazzolla Gatti, 2017; Cazzolla Gatti, 2018). Second, we make use of the framework to start organizing and discussing material published on the COVID-19 pandemic. Given the proximity and complexity of the events, preliminary scientific works are often published in news media before being filtered through peer-reviewed journals. Therefore, our exploration includes scholarly research found in pre-prints, preliminary reports, editorials, and journalistic pieces

in addition to peer-reviewed research. Reliance on this wide variety of resources should be taken with caution. Thus, this paper represents only a first step towards more integrated research efforts that may be adopted and further developed in future scientific work.

In the following, Section 2 provides a closer look at the concept of diversity in the total environment as an organizing framework to understand and deal with the COVID-19 pandemic; Section 3 looks at the pandemic from the perspective of the Geosphere, emphasizing its geochemical diversity; Section 4 deals with the pandemic in the Biosphere relying on insights from evolutionary biology and ecology and argues that, as a result of a depleted biological diversity, biological systems have a reduced capacity to respond to new sources of stress, such as a pathogenic agent; Section 5 unpacks the complexities related to the pandemic in connection to cultural, social, and institutional diversity of the Anthroposphere. By looking more closely into our societies, we can identify the deep reasons as well as possible ways to work with the pandemic.

Finally, we summarize the main lessons learned and emphasize the need to care for and protect human, biological, and geochemical diversity by interdisciplinary research efforts in order to be able to address future global diseases.

2. The pandemic and diversity in the total environment

Over three quarters of the terrestrial Biosphere and Geosphere have been reshaped by humans, i.e. the Anthroposphere (Ellis and Ramankutty, 2008; Ellis et al., 2010). As of the year 2000, the majority of the net sum of the terrestrial Biosphere is defined by human-altered landscapes allocated to agriculture and settlements, while 20% constitutes semi-natural environments (inhabited land minimally used for permanent agriculture and settlements), and less than 25% can be regarded as wild (Ellis et al., 2010). Human-concentrated environments are depleted in diversity, not only in terms of biological entities (Biosphere) such as plants, animals, fungi and bacteria, but also in terms of diversity at the chemical and molecular level within the Geosphere and at the biocultural level (Anthroposphere) in an increasingly globalized world. Consider, for instance, the impact of agriculture on the concentration of soil nutrients. Human activity in growing food crops has, for millennia, been recognized to displace essential nutrients faster than can be replenished, requiring soil fertilization and field fallowing (Mäder et al., 2002). Moreover, the uncontrolled spread of industrial agriculture and the land resources it consumes has displaced Indigenous communities and their access to native landscapes, resulting in the reduction of ethnic, linguistic, and cultural diversity (Burnside et al., 2012). In a human-modified landscape, the diversity of Biosphere, Geosphere and Anthroposphere have become impoverished and less resilient (Cazzolla Gatti, 2017). The increasing recognition of the lack of diversity and thus a reduced resilience of planet Earth as a symbiotic and self-regulating system - sustained by complex interactions across the Geosphere, Biosphere, and Anthroposphere - is essential to understand preconditions and processes leading to disease outbreaks.

It is against this background that we develop an intelligible and intuitive framework that relies on the idea of the total environment as an integrated and self-regulating system sustained by its biological, geological and anthropological diversity. This framework helps

to capture the complex interdependencies relevant for dealing with the COVID-19 pandemic without getting lost in the details of such interdependencies.

First, the framework emphasizes the numerous links that connect the three spheres in the form of feedback loops. Natural and social systems including those of the Anthroposphere, Biosphere, and Geosphere are governed by dynamic processes that regulate the system's state. Yet, rather than being governed by isolated and distinct responses, natural complex systems are usually regulated by coupled feedback loops resulting in even more complex dynamics (Cunningham and Cunningham, 2010). Feedback loops operate on input and output information, where information about any detectable change to the system (output) is determined and sent back serving as new input (Åström and Murray, 2008). This means the new input triggers rectifying processes that result in changes, which bring the system back to its regular state (i.e., set point). Negative feedback loops stabilize the system by buffering perturbations and keeping the system's internal environment relatively constant. On the other hand, positive feedback uses information gained about a system's output to reinforce changes that accelerate the transformation of the system in the same direction as the preceding output (Åström and Murray, 2008). In this paper, we identify feedback loops that are essential to maintain biological, physicochemical, and geological environmental activities.

Second, the framework makes it possible to understand the pandemic as an evolutionary phenomenon that emerges from the interaction and co-evolution of the Anthroposphere, Biosphere, and Geosphere. We use the term co-evolution here to refer to the dynamic interactions connecting natural systems, such as those in the Geosphere and Biosphere, and human-made systems in the Anthroposphere, such as social systems and technological systems (Norgaard, 1984, 1995). Co-evolution refers to the mutual change of system components over time. Co-evolutionary dynamics involving the three spheres take place across different time scales, especially in relation to the generation and maintenance of diversity. Whereas geochemical and mineral diversity in the Geosphere, for instance, is generated over billions of years, biocultural and socio-economic diversity has emerged over a timescale of thousands

of years. By emphasizing the evolutionary and co-evolutionary dynamics characterizing the total environment, the framework allows for considering both pre-conditions and implications of the COVID-19 pandemic at all sphere levels. We depict co-evolutionary dynamics that contribute to the reciprocal interplay within and between spheres in relation to the COVID-19 pandemic in Fig. 1.

The framework we apply/use focuses on some of the relevant feedback processes that contribute to the current COVID-19 pandemic. We highlight that positive and negative feedback loops as well as co-evolutionary dynamics are described here in naturalistic, not normative terms. For example, despite the clearly negative consequences for human diversity in the Anthroposphere, propagation of SARS-CoV-2 may be considered a process of positive feedback to preserve and even increase biological and geological diversity in the Biosphere and Geosphere.

Following these initial lines of argument, we proceed to explore the relations between the pandemic and the three spheres. We rely on insights from recently published contributions and show how the framework above can help to generate a deeper understanding of the COVID-19 pandemic by emphasizing interconnections and processes across the three spheres. As an exhaustive approach exceeds the aims of this contribution, we identify, for each sphere, entry points through which to understand the systemic nature of the COVID-pandemic from the perspective of the total environment and emphasize the importance of focusing on the role of diversity within and across the three interconnected spheres.

Simultaneously, the feedback from the pandemic to the Anthroposphere implies a decrease in human growth and activity, which concurrently confers feedback on the Biosphere and Geosphere as influences with regard to the total environment. The timeline in the lower part represent the emergence of diversity over time.

3. The pandemic and the geosphere

The impacts on the geochemical diversity of the Geosphere may affect the COVID-19 pandemic. Human activities have significant impact on the Geosphere, such as (for example) accelerating desertification, causing soil acidification or anoxic conditions in oceans and lakes,

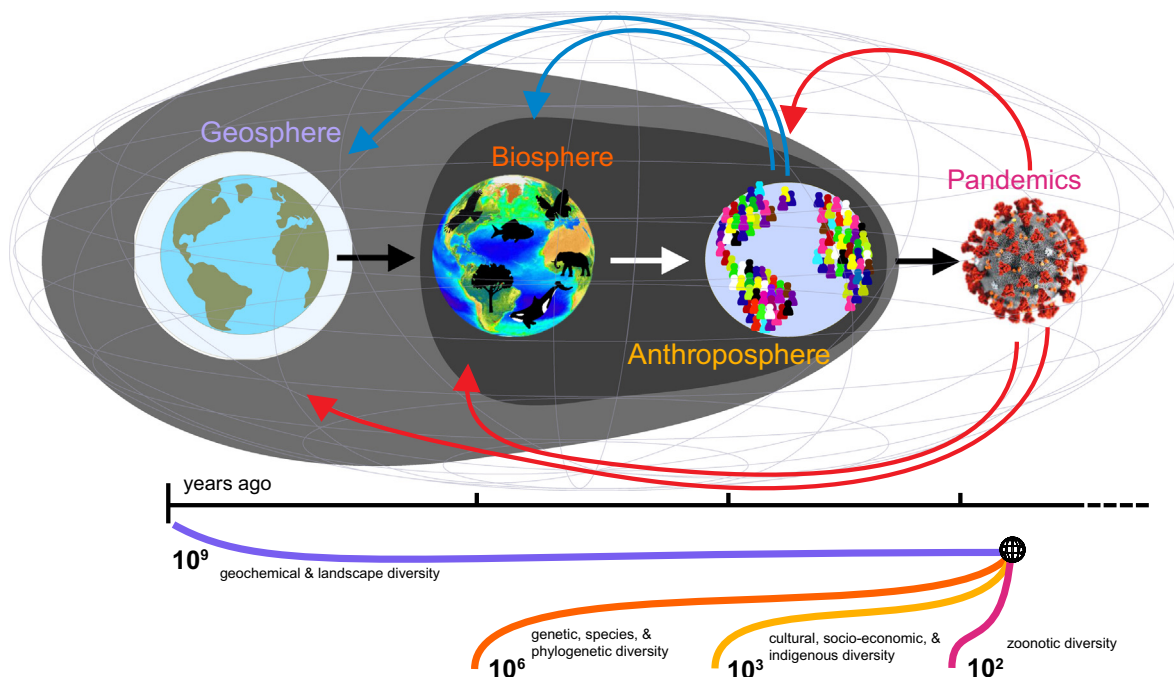


Fig. 1. The complex relationships between the pandemic and the different spheres are shown by inferred forms of feedback (blue arrows from the Anthroposphere, red arrows from the Pandemics), which in turn impact one another (black and white arrows). The feedback from the Anthroposphere to the Biosphere and Geosphere comes back as triggers that created the conditions for the emergence of the pandemic. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

increasing greenhouse gas emissions, and altering rainfall and drought patterns. These processes destabilize the natural landscapes and globally have led to devastating cycles of depletion and environmental destruction. In this section, we review some of the material recently published on the COVID-19 pandemic in accordance with the three sub-spheres of the Geosphere, namely the Atmosphere, Hydrosphere, and Lithosphere.

3.1. Atmosphere: air and its relation to COVID-19

Arguably, the relationship between the atmosphere and the pandemic is straightforward given the respiratory nature of COVID-19. Atmospheric factors most strongly linked to exacerbation of the pandemic relate to air pollution. For example, volatile particulates may be carriers of the virus, enhancing its persistence in the atmosphere (Setti et al., 2020). Air pollution may also be a cofactor in mortality rates (Conticini et al., 2020; Wu et al., 2020), and scientists understandably expressed concern about the summer wildfire season (Gerencser, 2020) and crop residue burning (Singh, 2020; see also Chakrabarti et al., 2019). On a larger scale, debates prevail about the impact of climate change on the intransient nature of the pandemic. The foreseeable intersections of climate hazards – enhanced under climate change – with COVID-19 outbreaks may have devastating consequences (Phillips et al., 2020). Still, local weather conditions (temperature and humidity) have been discredited as main factors that affect the rate of transmission (Luo et al., 2020).

One of the most evident impacts resulting from human activity is the increased atmospheric carbon dioxide (CO₂) content from 280 ppm of the pre-industrial age (the year 1750 chosen as the baseline related to changes in long-lived, well-mixed greenhouse gases in the Holocene) to more than 400 ppm in 2017 (NOAA-ESRL, Mauna Loa Observatory, 2017). Within just a few centuries, our species has released carbon stores from the ground that took millions of years to accumulate (Steffen et al. 2007). We have exponentially increased urbanization (Seto et al., 2012) and pollution that contaminates even the poles and the deserts, some of the most remote areas of this planet (Cózar et al., 2017). A recent study showed, with a very high accuracy thanks to the use of multivariable importance classification conducted with big data and artificial intelligence, that prolonged exposure to air pollution (especially to fine particles) has contributed to SARS-CoV-2 mortality and infections in Italy (Cazzolla Gatti et al., 2020).

Simultaneously, the socio-political reactions to the pandemic have had a significant counteractive impact on the atmosphere, especially with regard to pollution. Major sectors of industrial activity have been shut down, lockdowns have been declared in major cities the world over, and air traffic has been massively reduced. As a consequence, carbon emissions have been reduced, along with other toxic gases and particulate matter (Patel, 2020; Wang and Su, 2020; Cazzolla Gatti, 2020a; Isaifan, 2020; Le Quéré et al., 2020). For example, the lockdown response to the COVID-19 caused a reduction of nitrogen dioxide (–60%) and particulate matter (–31%) levels in 34 countries (Venter et al., 2020). Forced lockdowns also decreased the emission of particulate matter at the regional level from mining related activities like stone quarrying and crushing (Mandal and Pal, 2020). Hence, some scientists optimistically view the pandemic as an opportunity to implement drastic changes that might alleviate climate change and entrain a more sustainable globalized society (Rosenbloom and Markard, 2020; Schwartz, 2020). Nonetheless, large countries have implemented measures that go in the opposite direction, linking environmental deregulation with economic revival (Tollefson, 2020; Holden, 2020). In fact, some major cities are already returning to pre-COVID-19 levels of air pollution (Carrington and Kommenda, 2020).

3.2. Hydrosphere: water and virus, a hidden link

Two patterns of interaction between the hydrosphere and the current pandemic are noticeable. The first is the critical role that access to

water plays in controlling the spread of the pandemic. It is well documented that frequent handwashing with soap and water is a basic but effective way to prevent the spread of the SARS-CoV-2 (WHO, 2020a, 2020b, 2020c). However, large sections of the population have limited access to clean water (Otto et al., 2020), which, especially in wealthy developed nations, is a product of wealth and racial inequality (Bakker, 2010; Deitz and Meehan, 2019). This makes socially vulnerable and marginalized groups even more susceptible to COVID-19 outbreaks (e.g., Hyde, 2020). Water scarcity – partly induced by climate change – builds on such structural problems and amplifies risks (Al-Masri, 2020). In addition, untreated wastewaters may be a significant factor in disease transmission, especially if enteric transmission of the virus is confirmed (Heller et al., 2020; Ahmed et al., 2020a, 2020b; Lodder and de Roda Husman, 2020). While there might be less water pollution recorded (Khursheed et al., 2020) – at least in the short term due to lower economic activity, industrial production, and resource use – an increasing number of studies report the molecular detection of SARS-CoV-2 genetic material in wastewater. An overview and comparative details are provided by Kumar et al. (2020a) and Kitajima et al. (2020). Wastewater treatment plants may not completely eliminate the genetic material of SARS-CoV-2 and, therefore, potentially lead to further transmission through wastewater (Kumar et al., 2020b). However, more research is needed to fully understand the role of wastewater in SARS-CoV-2 transmission (Kitajima et al., 2020). This highlights the crucial role that access to clean water has in fighting and containing the pandemic.

The second pattern is the change in pollution regimes in the hydrosphere due to the reduction in commercial and leisure maritime traffic amidst the current pandemic. As a result, a decrease in the rate of water pollution – including underwater noise pollution – has plummeted (see, e.g., Thomson, 2020; Randall, 2020; McVeigh, 2020; Chow, 2020; Yunus et al., 2020). Quantitative impacts are also being recorded in terms of rising groundwater tables in water-scarce cities as commercial extraction services are suspended (DHNS, 2020). Although overall pollution in the hydrosphere seems decreased, the actual scale of that reduction is still unknown.

3.3. Lithosphere: the ground floor of geology in biology

The lithosphere, or broadly speaking, the Earth's crust, is intertwined with the pandemic, its origins, and its spread. While most links between the lithosphere and the pandemic are brought on by human activities in environmental modification – e.g., mining, deforestation, river dredging – some have proposed a more direct connection. The main factor is how humans interact with the lithosphere. Extractivism in the lithosphere amplifies the risk of pandemics. On the local scale of extraction, people working in and living around mining areas experience the reduction of forested areas (Vaglio Laurin et al., 2016; Sonter et al., 2017; Ranjan, 2019) and rapid changes to the ecosystems (de Quadros et al., 2016; Gatti et al., 2017, 2019), with the resulting ecological stress leading to habitat destruction and, consequently, closer contact between humans and wildlife, which in turn increases the emergence of zoonotic diseases (Walsh et al., 1993; Cascio et al., 2011; Quammen, 2012). On a global scale, extractivism provides resources – particularly fossil fuels – which enable global connectivity, enhancing the risk of global pandemics (Barak, 2020). Geosphere resources provide human communities with the means to their economies and their activities extending beyond their geological zone, and the depletion of these resources, and moreover, their conversion into polluting waste reduces productive and regenerative aspects of the Biosphere. The result is a decrease of natural habitats for animals and plants and consequently a decrease in biodiversity, which provides the breeding grounds for zoonoses.

Our perspective is that the emergence of the pandemic has the effect of counterbalancing human activities, forcing a stall in production and mobility, and represents an aspect of the total environment equilibrium.

Some of these effects are immediate and local, such as decreases in seismic noise, most likely due to a decrease in industrial activities and transportation in urban settlements (Gibney, 2020). Other effects are more widespread, such as economic lockdowns and the decrease in international traveling (e.g., WTO, 2020; Garver, 2020; Gopinath, 2020) relaxing demand for fossil fuels or minerals and thus their extractive activities. However, these correctives are only immediate effects. As a consequence of a reduction in state or corporate organized activity, there is a surge in illegal mining operations across the world (Hall, 2020). These activities have the potential to spread the virus beyond large-scale built environments, and to Indigenous communities, whose exposure to the pandemic has otherwise been relatively limited (Ruiz Leotaud, 2020). In the mid-term, the pandemic might intensify extractivism. Indeed, to revitalize economies that are experiencing a slowdown, environmental regulations have already been weakened so as to accelerate extractivism in some of the major countries in the world, such as India and the US (Gokhale, 2020; Miller, 2020). While evidence of the short-term impact of the pandemic on the sub-spheres of the geosphere already exists, the implications of this evidence for the medium and long-term dynamics of the total environment require further study and greater inter- and transdisciplinary efforts.

4. The pandemic and the biosphere

In identifying instances of human impact on the diversity of the Biosphere as examples of anthropogenic stress and ecological fragmentation, we emphasize the interactions between the pandemic and the Biosphere using an evolutionary perspective based on ecological, evolutionary, and developmental considerations (Eco-Evo-Devo). Environmental factors are in constant interaction with organisms' diversity (both, on the level of genotypes and phenotypes) and can induce variation for natural selection to act upon (Abouheif et al., 2014). We employ this perspective to discuss the mutual influences between the pandemic and the Biosphere: first, we identify past records of anthropogenic stress on biological and ecological diversity as preconditions of the ongoing pandemic; second, we provide examples regarding the current pandemic's interactions with the diverse components of the Biosphere; and third, we consider the COVID-19 pandemic in relation to future exploitable environments (i.e., viral transmission through a new host) observed in various perturbed ecosystems that experienced a diversity loss.

4.1. Past impacts on biological diversity facilitated the emergence of pandemics

Using information garnered from past or ongoing instances of ecological perturbation allows us to visualize outcome scenarios, both short- and medium/long-term, for the situational environment of the pandemic and how humans and other species may be affected given the compromised resiliency of the Biosphere. From prior contexts, many examples exist that showcase the pathway from human management to eutrophication to eventual reduction in species richness, leading to homogenization of landscapes and fragmentation of natural habitats (Marini et al., 2008). Such disturbed environments constituted a fundamental precondition for the emergence of pathogens, like SARS-CoV-2. Major disruptions to continental fauna can be attributed to human ancestors, going even as far back as to Acheulean-wielding early *Homo*, since it was observed that Middle Pleistocene extinctions in Africa mirrored extinctions in North America at the end of the Pleistocene. However, a thorough review concluded that the evidence is not soundly in support for an anthropogenic cause of the African megafauna decline during and prior to the Acheulean techno-complex era (Faith et al., 2020). Rather, fully modern humans are uniquely to blame as non-geological precipitators of continental-scale extinctions (Barnosky et al., 2011), restricting the earliest dates of significant ecological disturbances to the emergence of our species between 300,000

to 200,000 y BP (Hublin et al., 2017; Shea et al., 2007; White et al., 2003). There is strong evidence that biodiversity loss and ecosystem simplification favors both new virus–host encounters and new epidemiological dynamics resulting in the emergence of pathogens (Roossinck and García-Arenal, 2015; Brooks et al., 2019; Gibb et al., 2020), as exemplified by the current COVID-19 pandemic.

Most scientists agree that human activities during this Anthropocene era have accelerated the rate of species decline that is causing the Earth's sixth major extinction (Leakey and Lewin 1995). The current extinction rate remains controversial but it oscillates between 100 and 1000 times the normal background rate of extinction (Kolbert, 2014). This mass biodiversity decline event is underway as a result of the anthropogenic impact on ecosystems, which includes human overpopulation, pollution, overexploitation of natural resources (for instance deforestation and overfishing), and the emission of greenhouse gases (GHG), etc. Some evolutionary biologists and ecologists propose that anthropogenic environmental disturbance has reached a tipping point since a high number of animal and plant species that lived on Earth immediately before the Anthropocene are already extinct, threatening the basis for human existence (Zalasiewicz et al., 2008; Kolbert, 2014). This recent mass extinction represents a likely facilitator for the emergence of new pathogens, like the current SARS-CoV-2 outbreak. It is well-known that biodiversity loss increases the incidence of emerging diseases (Keesing et al., 2010) and enables disease proliferation (Pongsiri et al., 2009). Once again, these negative consequences (from the perspective of human life) actually work to reduce the driving destructive force of human activity, thereby countering anthropogenic changes and contributing to equilibrium. Environmental exploitation, depletion, and destruction have devastating consequences for the sustainable ecology that supports all life, and eventually even human technological buffers are breached. For instance, the emergence of major vector-borne diseases (e.g., malaria, leishmaniasis, Chagas) has been linked to several anthropogenic impacts, including urbanization and deforestation, human population growth in both developing and developed countries, increased global trade of wild animals, and climate change (Colwell et al., 2011).

Focusing on the present pandemic situation, we can see how human activity directly influences other life in the Biosphere. Due to the likely origin of SARS-CoV-2 as a zoonotic disease linked to habitat destruction and wildlife consumption (e.g., Ahmad et al., 2020; Anjum, 2020; Bonilla-Aldana et al., 2020; Cazzolla Gatti, 2020a; Colwell et al., 2011; Frutos et al., 2020; Gibb et al., 2020; UNEP, 2020), investigating the relevant interactions between humans and the Biosphere is crucial for understanding the disease emergence and designing measures towards its containment. Past outbreaks of zoonoses involving domestic or wild animals – e.g., BSE (Adkin et al., 2010), bird flu and SARS (Yang et al., 2007), or the bubonic plague (Nelson et al., 1986) – have had significant consequences regarding our use of, and attitudes towards the affected animal species as well as ecological consequences for natural and human-made habitats (Van Hoof et al., 2006; Yeloff and Van Geel, 2007). Initiatives such as the United Nations Environment Programme (UNEP, 2020), the DAMA protocol (Brooks et al., 2019) or the “One Health” concept (Bonilla-Aldana et al., 2020) emphasize the interconnections between human health, animal health, and the integrity of the ecosystem, and advocate for international and interdisciplinary collaborations involving NGOs as well as academic, medical, governmental, veterinary and agricultural institutions.

4.2. Current biodiversity exploitation and the COVID-19 pandemic

Many academic papers and preprints as well as journalistic contributions highlight aspects of mutual influence between the COVID-19 pandemic and elements of the biosphere (e.g., Daly, 2020; Dehghani and Kassiri, 2020; Kray and Shetty, 2020; African Renewal, 2020; Kretchmer, 2020; Martin, 2020). These publications primarily feature animals that are particularly vulnerable to anthropogenic stress due to their roles as potential vectors, livestock, pets or game, or their distribution in urban

environments as well as areas shaped by tourism. The following examples acutely demonstrate how human-mediated ecological fragmentation puts both humans and animals at risk.

The spate of news stories in the Spring of 2020 about zoo animals testing positive for COVID-19 brought attention to the potential of wild and captive animals as disease transmission vectors, which are more prevalent when buffer zones between human and wild environments are thin or altogether destroyed. Numerous researchers and conservationists have called for increased protective measures for primates, especially wild and captive great apes, which may be susceptible to the virus (Craig, 2020; Gillespie and Leendertz, 2020; Melin et al., 2020; Richardson, 2020). Captive animals in frequent contact with humans exhibit high risk. For instance, eight tigers and lions at the Bronx Zoo have tested positive for SARS-CoV-2 after showing mild respiratory symptoms (Daly, 2020). Similarly, symptomatic infection and increased mortality of mink have been reported from pelt farms in the Netherlands and are even suspected to be able to transmit the virus back to humans, resulting in shutdowns of mink farms and mass euthanasia of animals (Maron, 2020b, 2020c; Oreshkova et al., 2020). These examples showcase the risk of non-human reservoir hosts establishing themselves in the wild and the danger of future zoonotic outbreaks (Bonilla-Aldana et al., 2020; Gibb et al., 2020). The same is true for popular companion animals.

Cats and dogs cohabitating with infected humans have both been tested positive for the virus; however, the number of cases is low, most animals are asymptomatic, and there is currently no evidence that they themselves can effectively transmit the virus to humans (Almendros, 2020; Gorman, 2020; Halfmann et al., 2020; Shi et al., 2020; Sit et al., 2020). For a number of common synanthropic animal species, Shi et al. (2020) found that “SARS-CoV-2 replicates poorly in dogs, pigs, chickens, and ducks, but ferrets and cats are permissive to infection.” While most recent research on the pathogen's zoonotic origin and transmission focuses on the implications of human interaction with wild or domestic vertebrates, synanthropic insects have also been hypothesized to contribute to the spread of COVID-19: Though definitive data are still lacking, flies and cockroaches are suspected to spread viral particles present on surfaces or in human feces by mechanical transmission (Dehghani and Kassiri, 2020). While mosquitoes are not known to be vectors of SARS-CoV-2, increased local population density and reduced mobility due to lockdown measures in densely populated areas of the global South (Sun et al., 2020a, 2020b) indirectly increase the probability of infection with other mosquito-borne diseases, such as malaria, Chikungunya and Dengue fever (Jindal and Rao, 2020). This risk, along with the wish to eliminate insects as potential mechanical vectors, will likely necessitate an increased use of chemical insecticides within or close to human living spaces (Dehghani and Kassiri, 2020; Jindal and Rao, 2020).

Although the pandemic has produced negative feedback on human activities (Anthroposphere), which produced immediate benefits to the Biosphere and the Geosphere (Cazzolla Gatti, 2020a), the economic fallout of the global halt in production has meant that in some regions, particularly in the global South, the support for safeguarding wild habitats from destruction dried up.

Precarious living conditions, reduced vigilance, and restricted movement have led to an increase in poaching, deforestation, and a decrease in cross-borders cooperation, exemplified by the inability to control locust plagues, that normally would enable better environmental protections (African Renewal, 2020; Kray and Shetty, 2020; Lindsey et al., 2020; Price, 2020). In Botswana, for example, rhinos have been poached in tourism hotspots (Newburger, 2020). By contrast, the conditions of the pandemic have made whaling unprofitable in Finland, leading instead to protection efforts and increased popularity of whale watching (Mulvaney, 2020) concurrent with trip cancellations by shipping or cruise companies. The resulting underwater noise reduction may have a positive effect on various cetacean species who rely on acoustic communication (Vergara, 2020; Vergara et al., 2019).

Human activity around the world has dramatically decreased within the past months – a phenomenon widely perceived to reduce human-made stress and thus benefit nature and wildlife due to less noise and pollution, allowing reclamation of contested habitats, at least temporarily. In France's national Parc des Calanques, sightings of animals have increased since the park has been closed during the pandemic, even including two fin whales observed close to the coastline (Daddi, 2020). Similarly, mountain goats in northern Wales have wandered along empty city streets and grazed in people's gardens; wild boars were spotted within Barcelona (Spain) city limits (Kussin, 2020; Kretschmer, 2020); a civet was sighted in the middle of Kozhikode (India); a puma was seen roaming through the center of Santiago (Chile) (Martinetti, 2020); and Indian beekeepers are reporting increases in the amount and quality of honey (Nigam, 2020). However, in some cases the economic paralysis and lockdowns due to the pandemic have also been detrimental to urban wildlife: numerous news stories report city-dwelling monkeys and pigeons – hitherto dependent on food from tourists – scavenging and even facing starvation (Kretschmer, 2020; Martin, 2020).

4.3. Future directions of human evolution and biosphere exploitation

By examining the features of the biosphere from a principally fundamental-unit based approach – extrapolating from molecules to organismal ecological scales, and applying what can be inferred from other examples of perturbed ecologies (such as invasive species or ecological fragmentation) to the globalization of anthropogenic environmental modification, and we can help explain the pandemic given the prior insights about the ontogeny of organismal proliferation in an exploitable environment (in this case, viral transmission through a new host) observed in various perturbed ecosystems. In human-occupied environments, the diversity of the Biosphere, from molecular building blocks to mammals, is narrow and accommodates a minimum range of biological activity, contains few redundancies, and tends to be depleted in competitive interactions between organisms. What these previous examples point to is that humans, on account of our built environments that compress natural diversity from the bottom up, are especially vulnerable to stressors from a highly disruptive, pandemic-causing, infectious agent (SARS-CoV-2). The concept of stress biology is widely studied in cell physiology and is seen as a ubiquitous and essential part of any organisms' life cycle (Wagner et al., 2019). It can be described as disturbance of physiological stability, while the response to stress plays a role in compensating for physiological disturbances and in re-establishing equilibrium. The questions then become: i) when is stress response triggered to control homeostasis (rheostasis); and, ii) when do stress responses overshoot, causing irreversible reactions in a system?

From the molecular scale all the way up to the organismal and macro-ecological level, there is a cumulative impact of destabilizing stressors. When these stressors accumulate without a competitive signal (i.e., multiple inputs that can disperse the trigger for a reaction) – due to human-engineered environments that selectively suppress variability normally present in naturally diverse ecosystems – then an aggressive and overwhelming response can occur, as seen in severe COVID-19 cases. This model of understanding helps to explain the uneven distribution in the rate of intensive or fatal COVID-19 cases in which the immune system overreacts to a wide-spread viral infection, implicating a stimulus-poor ontogenetic environment. The process of stimulus-induced developmental maturation is exemplified by studies on environmental enrichment and promotion of brain plasticity in the recovery of function (Baroncelli et al., 2010), and by evidence that perturbed microbiome development in early life can establish long-term susceptibility to autoimmune diseases (Amenyogbe et al., 2017). With appropriate training, the immune system should activate primarily against the foreign agent and only in a limited manner against the self. This aligns with the observation that clinically immunocompromised

people are at greater risk for severe infections as their impaired immune system is severely challenged by pathogens. In addition, imbalances in human gut microbiota during development could also explain the higher risk for subclinical portions of the population (the seemingly unpredictable severe cases) as gut microbiota regulate key antioxidants of the host. Deficiencies of antioxidants due to ontogenetic microbiota imbalances contribute to oxidative stress response in the host (Polonikov, 2020), concomitantly suppressing the adaptive arm of the immune system (i.e., leading to a lack of T-cells required for killing virus-infected cells). The combined effects of an insufficient cell-mediated immune reaction and an overwhelming production of reactive oxygen species mediating oxidative stress response then cause local or systemic organ damage leading to the pathogenesis of severe COVID-19.

Given the evolutionary perspective and our premise that diversity reduction in the Biosphere is the fundamental characteristic of human-occupied (near global) environments, then humans are the arbiter of their own pandemic – irrespective of the release of a novel viral agent into the Anthroposphere. Human machinations in ecosystem engineering are unquestionably inferior to evolutionary processes. Human-modified environments are disruptive to the natural mediating functions that support balance in development, given a sufficiently stimulus-rich setting. This view is further supported by current research in modern evolutionary biology that increasingly sheds light on the role of biodiversity in promoting compensatory feedback interaction between stress response and gene regulatory networks (Zhou et al., 2020). When biodiversity is constrained, buffering mechanisms regulating the expression of variation on phenotypes also breakdown. The absence of competitive signals results in fewer opportunities for regulatory feedback to generate a robust stress response, which in different conditions would have buffered genetic and environmental perturbations.

The Biosphere surrounding nodes of human activity is inherently fragile, and human societies have long been ripe for pandemonium from an exploitative disease agent (Cheng et al., 2007; Afelt et al., 2018; Brooks et al., 2019). Humans are too numerous, too mobile, and, more importantly, too voracious for the planet's resources (Cazzolla Gatti, 2016). These are the conditions in which population growth is normally constrained by the environmental carrying capacity (Cohen, 1995) and threatened by infective diseases (Jones et al., 2008), which spread with ease in overpopulated areas (Cazzolla Gatti, 2020b).

To possibly prevent even more far-reaching and disastrous long-term impacts of human exploitation on the Biosphere, many researchers are currently calling for concrete actions that consider the interdependencies of humans, animals and ecosystems: Stricter regulations on the use of wildlife in food or traditional medicine, increased safety measures to avoid contact between wild animals and livestock, and stronger emphasis on the management and conservation of wildlife reserves may help to mitigate the current situation and avert future zoonotic outbreaks (Bonilla-Aldana et al., 2020; Frutos et al., 2020; Lindsey et al., 2020; Maron, 2020a, 2020b, 2020c; Newburger, 2020; Wei, 2020; Maron, 2020a, 2020b, 2020c; UNEP, 2020). Similarly, there is a growing awareness of educators on including ecological complexity, philosophy of science and scientific literacy in school curricula when treating the COVID-19 pandemic, aiming to introduce younger generations to the complex connections between the spheres and promote critical thinking (Reiss, 2020).

5. The pandemic and the anthroposphere

The Anthroposphere is a diverse, complex, and multi-scale system in which biological and socio-cultural agents interact and mutually influence each other over time. Within the biological and ethnic diversity of the Anthroposphere, human agency, from individuals to societal and formal decision-making at the national and global levels, contributes to shaping emergent processes. To organize material published about the COVID-19 pandemic in the realm of the Anthroposphere, we make use of a multi-level approach that captures interconnections

across agents ranging from individuals to global organizations. The micro-level focuses on individuals and introduces how the pandemic relates to psychological and behavioral diversity. The meso-level emphasizes the consequences of the COVID-19 pandemic on the diversity of minorities and disadvantaged groups as well as on pre-existing systematic gender bias. Finally, the macro-level considers decision-making processes at the level of single nation states as well as at the level of transnational organizations.

5.1. Micro-level: impact on psychosocial, behavioral, and domestic dynamics

The COVID-19 pandemic and the quickly-adopted lockdown measures intended to slow down its spread have had a significant negative impact on people's mental well-being. Fear of the unknown, shortages of therapeutics, drastic public health measures that challenge notions of personal freedoms and the need for social connections, large economic and financial losses, mixed messaging from authorities, and long-term uncertainties trigger anxieties that create emotional distress, and an increased risk for psychiatric illness associated with COVID-19 (Pfefferbaum and North, 2020). Among the psychosocial symptoms of the COVID-19 pandemic, small effects foretell significant long-term trauma, including, but not limited to shifting moods, negative self-thoughts, invasive memories, irritability, trouble sleeping and focusing, anxiety, avoidance, anger, detachment, depression, alcohol abuse, and fear (Torales et al., 2020; Venuleo et al., 2020; WHO, 2020a, 2020b, 2020c). On the other hand, however, some individuals with preexisting psychological conditions (e.g., social anxiety) have experienced alleviation of symptoms during isolation (Bradley, 2020). Such psychological distress in association with the current pandemic is not confined to specific geographic regions but likely affects people all around the world (Qiu et al., 2020; Toledo-Fernández et al., 2020a, 2020b). Distress symptoms seem to last longer than two weeks, as was initially predicted, extending up to two or three months (Yong, 2020).

Due to the many stressors linked to social isolation as well as societal demands put on essential workers, increase in Post-Traumatic Stress Disorder (PTSD) symptoms has become an additional public health problem (Pfefferbaum and North, 2020). Particularly, healthcare workers providing frontline services, people who have lost their jobs, or victims of domestic violence are most likely at greater risk for developing long-term adverse psychological problems (Cai et al., 2020; Chen et al., 2020; Shah et al., 2020). Additionally, when pre-existing social disparities coincide with psychosocial and behavioral changes due to social distancing, negative impacts afflict not only the well-being of the individuals affected, but also that of their closest social environment (i.e., family or cohabitants).

Dysregulated (poorly modulated) emotions in combination with regular alcohol and/or narcotics consumption can increase violent behavior, especially within family environments (Bradbury-Jones and Isham, 2020; Peterman et al., 2020).

Domestic abuse of, and sexual violence against women, children, and LGBTQ+ individuals are intensified in the context of lingering patriarchal biases, and often exacerbate health and political emergencies (e.g., disease outbreaks, war; Van Gelder et al., 2020). During the current COVID-19 pandemic, for example, calls to domestic abuse helplines increased by 50–130% in most Latin American countries during the first week of quarantine (Ortiz, 2020; Sigal et al., 2020; Marques et al., 2020). A major reason being that quarantine and lockdown situations confine victims of domestic abuse in the same space as their aggressors, often for prolonged periods of time. Within this context, dynamics of power can be detrimentally amplified and distorted by those who abuse, often without scrutiny from outside (Bradbury-Jones and Isham, 2020). In addition to being cut off from social support (e.g., friends or helplines) due to the abuser's actions or the enforced quarantine measures, political and health emergency interventions often further reduce victims' access to social and health support services because what little funding exists is diverted to the pandemic emergency response (John

et al., 2020; Wenham et al., 2020). Prolonged maltreatment, abuse, and children's exposure to domestic violence may lead to complex PTSD and other pathological emotional, cognitive, and behavioral conditions that occur later in adulthood (Humphreys et al., 2020). Gender-based violence is known to increase women's mortality rates (John et al., 2020), affecting not only cis-women, but also transgender people and persons who do not conform to binary genders.

5.2. Meso-level: disparities between ethnic and social groups

Social and ethnic groups across and within different countries experience the COVID-19 crisis unevenly. This is shaped by existing health and socioeconomic disparities. Biological, geographical, and socio-economic factors mutually influence each other, resulting in compounded effects of increasing risk of infection and physical susceptibility in certain groups.

Comorbidities (i.e. the presence of one or more additional health complications co-occurring with a primary condition) have been shown to increase physical susceptibility to COVID-19. Among the comorbidities that have been associated with severe disease and mortality in COVID-19, the most prevalent conditions include hypertension, obesity, diabetes, cardiovascular, respiratory diseases, vitamin D and nutritional deficiencies (Garg et al., 2020; Hastie et al., 2020; Petrilli et al., 2020). The most strongly impacted age group are people over the age of 65 (Garg et al., 2020), which could be the result of both the progressive age-related decline of innate and adaptive immune responses (Koff and Williams, 2020; Poland 2018) and a higher prevalence of pre-existing diseases, which increases the likelihood of being severely affected by the virus. Some populations and communities have higher rates of a particular combination of comorbidities that increase their COVID-19 mortality rates (Kurian and Cardarelli, 2007). For instance, a gene cluster on chromosome 3 that was inherited from Neanderthals, and is present in ~30% of South Asians, ~8% of Europeans, and ~4% of admixed Americans, was described as a risk locus for respiratory failure upon COVID-19 infection (Zeberg and Pääbo, 2020). Similarly, individuals with African ancestry living in the UK and USA have a higher prevalence of diabetes, hypertension, asthma, kidney disease, and obesity (Dyer, 2020; Kirby, 2020; Yancy, 2020).

Other populations who have been displaced from their sovereign lands and resources, and who have been marginalized from receiving fair access to social services or a living means of subsistence, such as Indigenous peoples of the Americas and Australia, are more susceptible to developing COVID-19 due to their increased risk of acute respiratory tract infections, vitamin D deficiency, increased inflammatory burden, higher prevalence of cardiovascular risk factors such as insulin resistance and obesity, cancer, and kidney injury (Khunti et al., 2020; Smith, 2020). In addition, geographical and environmental factors such as latitude, altitude, and temperature seem to be associated with the number of infected cases. A large study based on individuals from 29 provinces of China showed a negative correlation when comparing altitude and latitude with the number of infections, and a positive correlation between the number of infections and variation in temperature (Sun et al., 2020a, 2020b; but see Wu et al., 2020).

Existing structural socioeconomic inequalities also contribute to some social groups' heightened vulnerability to infection with SARS-CoV-2, all of which influences the type and availability of economic opportunities, the distribution of rights, and access to services as well as financial and material resources within societies. These inequalities directly shape individual susceptibilities and morbidity (e.g., poor nutrition that impairs the immune system), thereby facilitating viral infections (Whittle and Diaz-Artiles, 2020). People with an unbalanced diet have micronutrient deficiencies that lead to increased risk of mortality, morbidity, as well as delayed recovery (Jayawardena et al., 2020). Poor-quality food is associated with nutritional deficiencies that can reduce immune responses against viral infections (Whittle and Diaz-Artiles, 2020). Inequalities linked to economic opportunities are particularly evident through the emerging economic category of "essential workers."

Essential workers are part of the societal workforce who perform vital tasks for maintaining the physical and social infrastructure for societies to continue to function at a basic level (Van Dorn et al., 2020). These are often low-wage occupations with few or no opportunity for social distancing, limited economic buffering capacity, and high levels of in-work poverty (Sparke and Anguelov, 2020). The unequal distribution of, and access to material resources to meet basic needs, such as shelter, water, and food are also shaping the pandemic. Particularly in urban areas, homelessness, limited physical space (Vieira et al., 2020), and poor-quality building materials (Wasdani and Ajneesh, 2020) limit the ability to adopt mitigation measures thereby increasing risks of infection and mortality while also exacerbating indirect negative impacts on individual wellbeing. Similarly, unequal access to services, particularly with fewer physical resources in rural areas (Patel et al., 2020a) and economic barriers for accessing health services in contexts such as the US (Smith and Judd, 2020) also influence the spread of the pandemic.

Finally, limited availability of communications services (e.g., internet) hinders access to information and opportunities for social connections that may be particularly important in lockdown situations (Ahmed et al., 2020a, 2020b). Some sectors of society also have limited rights that reduce individual options and the ability to influence their own wider social and physical environment, such as people in prisons and refugee centers (Ahmed et al., 2020a, 2020b). Limited legal rights can also detrimentally impact economic and livelihood security, e.g., leave entitlement, sick pay and redundancy processes, and tenure rights can also make some groups more socially vulnerable (Corburn et al., 2020).

Those aspects of socio-economic inequality produce disproportionate exposure of some social groups over others. A particularly stark example is that of gender. Although the numbers of infections, hospitalizations, and deaths are skewed towards men, which may relate to immunological (Conti and Younes, 2020) or lifestyle differences (i.e. healthful practices, stress management, and social support networks), women are disproportionately impacted in various other ways. Such effects might have long-term consequences for their mental and physical health and financial opportunities. First, there is a gendered workforce distribution, of which women make up the majority of healthcare workers, paid domestic workers, school and daycare staff, and retail workers (UNECLAC, 2020; Wenham et al., 2020) – all professions that put women at a higher risk of contracting the virus. This is especially true for the health sector, where there are often shortages of personal protective equipment, and (paid and unpaid) domestic work, both of which may involve intimate contact with infected people.

Furthermore, women in most countries still carry the majority of the care burden for the elderly and for children. With schools and daycares closed, and grandparents physically isolated, the time spent by women on child (and dependents) care has increased. School closures also mean that parents have to juggle their jobs alongside childcare and home-schooling. In heterosexual couples, where both partners do paid work, this often means that the job that brings in less income will be sacrificed. Due to the gender pay gap, whereby women earn on average 18.8% less than men globally (13.1–21.8% depending on world region; ILO, 2018), couples may be forced (or choose) to sacrifice the woman's career. At other times, prevailing gender norms of the "male breadwinner" and the "female homemaker" mean that men's careers are more likely to be prioritized regardless of income. Both have the potential to curb women's economic opportunities broadly, in the short and long-term scale. Moreover, women disproportionately make up single-parent households.

Single mothers might encounter tremendous difficulty in handling home-office work, childcare, and home-schooling during their normal working hours while schools are closed. Particularly, single mothers in low-wage service jobs struggle even more to earn a sufficient income to provide for their families when work volume and job opportunities drop during a lockdown.

Gender bias also impacts individuals other than *cis*-women. Several countries (e.g., Peru, Panama, Hungary) have recently instated official policies and passed laws that enforce binary and non-fluid understandings of gender, which intensifies the risks transgender and intersex persons face from harassment, discrimination, humiliation, and violence (Perez-Brumer and Silva-Santisteban, 2020).

Furthermore, socioeconomic inequalities can also interact with biological population-level differences. Results from studies conducted with data from public data banks show that participants with African, Asian, or Native American ancestry are at an increased risk to develop and die from COVID-19 compared to European or European-American participants (Baggett et al., 2020; Banerjee et al., 2020; Garg et al., 2020; Niedzwiedz et al., 2020; Patel et al., 2020b; Yancy, 2020). Despite their low population density, the Navajo nation – the most numerous of the USA Native peoples –, the Isleta Pueblo in New Mexico, and Cherokee nation in Oklahoma, comprise a higher percentage of the young COVID-19 patients and experience more severe symptoms than the US population average. This demographic skew of the pandemic results in a per-capita infection rate among Native people that resembles that of people living in high population-density areas (Kakol et al., 2020). Native groups in Latin America represent a large percentage of the total population in countries such as Bolivia, Brazil, Guatemala, Mexico, and Peru (Banco Mundial, 2015). Due to extremely poor living conditions and the scarce access to health care, on account of limited economic opportunities, these Native groups are particularly vulnerable to COVID-19 (Amigo, 2020; de Dios, 2020).

5.3. Macro-level: decision-making at the national and transnational level

Formal decision-making by governments constitutes dynamic, multifaceted processes that shape the distribution of resources, costs, and benefits between and within nations (e.g., between different social groups). Responses to the pandemic have varied across different countries, leading to a cascade of different decisions (and non-decisions) over time by government actors. The pandemic has accelerated formal decision-making, which is often considered an opaque and protracted procedure. Moreover, it has prompted scrutiny of formal decision-making processes not only in terms of what decisions are made in response to unfolding circumstances, but also when, how, and why decisions come about. Consequently, the influence of diverse factors such as past health and economic crises (Howarth and Verdun, 2020; Manderson and Levine, 2020), political ideologies (Marmot, 2020; Sparke and Anguelov, 2020), as well as scientific knowledge were taken into account by policy-makers. Global socio-economic activity is a major factor in disease transmission since the intensity of intercontinental transit increases the odds of pandemics occurring. Through trade and travels, globalization introduces nonhuman hosts and their pathogens into new contexts, from cities to rural areas (Brooks et al., 2019). The fast and unprecedented reach of the COVID-19 pandemic demonstrates the power of globalization and the associated risks with massive interconnectivity in spreading pathogens to pandemic level. It should also remind us of the responsibilities we carry to mitigate global systemic risks and to safeguard human health and life. The COVID-19 pandemic has exposed numerous defects in a world characterized not only by global connections, but also by presiding inequalities (Sohrabi et al., 2020).

While socio-economic inequalities enable unsustainable modes of production and consumption through an unequal distribution of environmental goods and burdens (Giljum and Eisenmenger, 2004), the pandemic related crisis amplifies those inequalities in the short as well as in the long term. And while there is now ample scientific evidence that the poorer regions ('Global South') in the world have supported the development of richer regions ('Global North') over decades by providing natural resources and labor (Dorninger et al., 2021), the current crisis adds to domestic and international inequality (e.g., Kim and Bostwick, 2020). Studies found that already-vulnerable

groups prior to the pandemic – including ethnic minorities, and marginalized or socially disadvantaged sectors of the population – suffered disproportionately from state-level responses to the crisis compared to the affluent or ethnic majority (Blundell et al., 2020). As of only half a year into the COVID-19 pandemic, the world has experienced the most severe economic recession and unemployment rate since World War II (Worldbank, 2020), and yet the top one percent maintained capital growth (Business Insider, 2020). Ultimately, what remains key for long-term social and economic stability in the midst of this crisis are the national and international dialogues between scientific and political citizenry, and the sound policy decisions by state actors.

Global health governance organizations have emphasized the need for increased capacities for early detection, tracing, and isolation of COVID-19 cases. The World Health Organization (WHO) was criticized for its lack of leadership in addressing the COVID-19 pandemic, especially in the early days of the outbreak (Boseley, 2020) and indeed massive deficits in pandemic preparedness were exposed. For instance, a lack of cross-sectoral collaboration, especially between animal and human health sectors hampered early warnings of the zoonotic origins of SARS-CoV-2 and impeded progress towards remedial solutions at local levels (Renda and Castro, 2020).

Furthermore, the health governance of many regional authorities failed to provide a coordinated strategy. The European Union (EU) agency dedicated to cross-border health threats (European Center for Disease Prevention and Control, ECDC) lacked harmonization to implement decisions across the EU states, which was exacerbated by the fact that recommendations from the EU are not binding for national authorities (Renda and Castro, 2020). There are many examples of the negative consequences of uncoordinated decisions taken by different countries. For instance, the lockdown strategy applied in Belgium, but not in The Netherlands, caused movement of people across these neighboring countries such that Belgian shoppers inundated Dutch stores in border towns, which facilitated the spread of the disease.

Another dimension in need of a transnational approach is coordination to protect migrants and asylum seekers. The scarcity of running water, sanitization, and the impossibility of physical distancing has led to hotspots of transmission vulnerability (Kondilis et al., 2020). During the COVID-19 pandemic, Venezuelan migrants in Colombia were caught within strained relations between municipal and national levels of government. The national lockdown in Colombia translated into acute job loss and homelessness among Venezuelan migrants without status due to their reliance on the informal economy (Guardian, 2020).

The cultural and socio-economic processes that create human inequalities mentioned above have contributed to widening the gaps in access to adequate health care and economic stability during the pandemic. In theoretical terms of dynamical systems, these processes contribute to complex negative feedback that causes population decline and an adjustment of the source of ecological pressure. In doing so, human agency accelerates feedback processes stemming from the Geosphere and the Biosphere that can couple with socio-behavioral dynamics within the Anthroposphere. This observation is particularly worrisome because it demonstrates that humans are contributing input that works to feed inequality that is amplified in the global pandemic. As a consequence of these dynamics, we also argue that human biocultural diversity is depleted, and together with it, indigenous and traditional knowledge about ecosystems and their management irremediably lost.

6. Pandemics and diversity in the total environment: lessons learned and steps forward

In this paper, we have introduced an analytical framework that makes it possible to look at the COVID-19 pandemic as resulting from regulation processes that include coupled positive and negative feedback loops as well as co-evolutionary dynamics involving the Geosphere, Biosphere and Anthroposphere. Furthermore, we have

used this framework to explore and organize insights from the burgeoning literature on the COVID-19 pandemic from multiple disciplines in ways that highlight the role of diversity in the functioning of Earth as a symbiotic and self-regulating system. We propose to look at the COVID-19 pandemic as negative feedback on human activity, thus reducing human proliferation due to the fact that virus propagation can continue in an exponential manner by means of positive feedback loops as long as there is a lack of human counteraction. It is to be expected that similar pandemic scenarios caused by other zoonotic pathogens will follow this process as the current Anthroposphere provides an ideal breeding ground for negative feedback on itself via zoonoses.

Although the COVID-19 pandemic is an emergent phenomenon of the total environment, it features a disease that mainly affects humans and primarily spreads by the way our globalized societies interact with the diversity of the total environment. This especially includes the way in which we make use of resources in the different spheres through our modern lifestyles, from industrial production and transnational trade to international mass tourism and travel. Therefore, interconnections between the Biosphere and the Geosphere in relation to pandemics will often – if not always – be mediated by the Anthroposphere. Focusing on the importance of interconnections within and across the spheres, we present several key messages on the overlapping implications of the pandemic and human activities on the Anthroposphere, Biosphere, and Geosphere.

1. *Human pressures on diversity in all spheres have created the preconditions for the emergence of the pandemic and set the stage for its drastic effects.* Anthropogenic impacts such as overpopulation, ecological fragmentation, ever-increasing depletion of the Biosphere's and Geosphere's diversity, socioeconomic inequalities, and health disparities have contributed not only to the emergence of the pandemic but also to its severe consequences for both our societies and the total environment.
2. *The depletion of geochemical, biological, and human diversity has resulted in an accumulation of destabilizing stressors impacting human activities and global governance strategies, as well as entire species and ecosystems.* Indeed, the pandemic has interacted with the total environment in complex ways and on multiple spatial and temporal scales. The accumulation of stressors affects the way in which human individuals, communities, nations, and transnational organizations are able to respond to or mitigate the extreme circumstances created by the pandemic, because the diversity lost in all spheres cannot be simply restored when needed.
3. *Immediate impacts of the pandemic on the diversity of the Anthroposphere – due to large scale quarantine regimes – may appear auspicious in the short term for the regeneration of the diversity of the Biosphere and Geosphere, but they have negative consequences in the long term.* After a temporary economic lockdown, resources are redistributed away from social justice policies and nature conservation but towards an exploitative economy, which may lead to negative medium to long term effects. Most affected regions are already returning to pre-COVID economic growth-centered agendas, pre-existing issues of social justice are exacerbated in many places and new pressures on bio-geo-chemical diversity are already emerging in the aftermath of the first wave of the pandemic.

The impacts of the pandemic on the individual spheres cannot be analyzed in isolation, particularly in an increasingly interconnected world. Failing to recognize these interactions, the overlaps between the Anthroposphere, Biosphere, and Geosphere with their diversity will inevitably lead to our inability to prepare for and face future global diseases. Therefore, we suggest that the integrated approach we present in this paper could be of use for both research and political institutions dealing with complex geological, biological, and human systems with the goal of preserving and restoring their geochemical, biological, and human diversity. By making use of the framework, it will be possible

to prevent and address the current and future challenges posed to our species and our planet not only by the current pandemic, but also by similar ones that already loom large.

Interdisciplinary research, including a better modeling of social, ecological, and economic systems can help us to better understand how to reduce the loss of biological, geological, and human diversity. Intergovernmental plans and scientific consortia (such as IPCC, IPBES, GEO-BON, etc.) may help in addressing the national and international priorities and policies to protect diversity.

However, it is often difficult to embrace a systemic view of life. One of the reasons is that this view is inherently multidisciplinary and it is difficult to integrate into the fragmented and siloed structure of most research institutions (Capra and Luisi, 2014). This inability of the current research system to deal with the complex phenomena related with geophysical, biological, and human diversity from a systemic and integrated perspective limits the capacity of researchers to generate knowledge that might help to make decisions, create policies, and develop actions and interventions to address complex phenomena, such as the COVID-19 pandemic. This pandemic has made it evident that the main challenges of today's world (i.e. biodiversity loss, sustainable economy, climate change, inequality, etc.) are all interconnected and interdependent. As we have sought to demonstrate in this discussion piece, all are systemic problems that require systemic solutions.

Overall, scientific research needs to address the pandemic and its effects on human societies from the consideration that diversity is not only a *value*, but that it may also represent a *solution*. A sustainable global society able to protect its diversity is one that can satisfy its needs and aspirations without diminishing the possibilities of future generations. This is a very important exhortation that reminds us of our responsibility to pass on to future generations a world with more diversity than the one we have inherited. In each of the three spheres of the total environment we can find examples not only of increasing loss of diversity, but also of ways in which this diversity can be preserved and fostered. In the Anthroposphere, indigenous people teach us how to steward ecosystems and make wise use of local resources while maintaining the diversity of the Biosphere and the Geosphere. Since the unique feature of Earth as a symbiotic and self-regulating systems is its inherent ability to sustain the diversity of all life, research should also contribute to help building sustainable human communities designed in such a way that their lifestyles, social systems, economies, built environments and technologies do not interfere with, but instead promote, the inherent ability of nature to sustain the diversity of life.

The COVID-19 pandemic clearly shows that global rehabilitation policies must be launched immediately to reinforce health security by restoring the complexity and diversity of ecological, social and economic systems to make them more resilient. In order to reorient the future, strategic alliances between environmental justice and social justice movements are needed. It is, therefore, fundamental that as scientists we join our forces with civil society's protests in defending the rights of human diversity and that civil society joins scientists in the struggle for the conservation of biological and geological diversity. It is imperative for us as human beings to understand that diversity represents the invaluable resource of that universal exception that we call Life.

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.

Acknowledgements

We would like to thank the Konrad Lorenz Institute for Evolution and Cognition Research (KLI) for providing a stimulating environment that fostered the conversations and collaborative writing that led to this paper. We also thank Amitangshu Acharya from the Institute of Geography,

School of GeoSciences, University of Edinburgh, U.K. for his help in discussing some ideas of this paper during his fellowship at the KLI.

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