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COVID-19: Understanding Novel Pathogens in Coupled Social–Ecological Systems

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Abstract: The emergence of SARS-CoV-2 and the spread of COVID-19 is explored using a social-ecological systems (SES) framework. From an SES perspective, the pandemic is the outcome of feedback loops and cascading interactions within an anthropologically disturbed system. However, the SES framework tends to overemphasize human agency as drivers of system disequilibrium. Drawing on posthumanism theory in social science, the agency of the non-human world also plays a critical role in disturbances in SES. Non-human agency is incorporated into the SES framework, applying it to the emergence of SARS-CoV-2 and the spread of COVID-19, and public health responses. The paper is interdisciplinary, and a non-systematic literature review was combined with Socratic dialogue to examine how human-induced changes trigger feedbacks in SES, such as SARS-CoV-2. The non-human world, embedded within a coupled system of material relations; the natural/biological element, that finds expression in the emergence of SARS-CoV-2 and in generating the genome novel recombinant, which aligns with the conceptualization of the non-human as "vibrant", all play a role in shaping systems dynamics. This calls into question the anthropocentric view that human agency has the capacity to drive ecosystem dynamics. The implications for SES theory are discussed and we conclude with a case for a new ethics of interdependency to better serve SES analysis. The implications for practice, particularly considering projected future novel virus outbreaks, are discussed.

Keywords: Anthropocene; pandemic; agency; posthumanism; non-human agency; public health; ethics

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1. Introduction

On 11 March 2020, the World Health Organization (WHO) declared that COVID-19, caused by the spread of the novel virus SARS-CoV-2, satisfied the criteria to declare a pandemic. Using a social–ecological systems (SES) framework, this paper examines both the emergence and spread of the virus, demonstrating the multi-faceted, "coupled" relationship between ecological and social systems. This shows how the pandemic is a demonstration of the continuous changes to the fragile interface between the social and the ecological worlds. However, the pandemic also draws our attention to the need for the SES framework to adequately account for the agency of non-human nature in shaping societal events. To this end, theoretical developments in posthumanism are drawn into the analysis.

The paper begins with a critical discussion of recent SES literature, where we note an anthropocentric focus and draw upon parallel scholarship that considers, in a more direct manner, the agency of non-human nature. While the classic SES approach gives emphasis to "nature", especially understood in terms of ecological processes, there has been a tendency over time to over-emphasize the influence of human agency. Recent developments in social science theory, in particular posthumanism, provide an excellent theoretical approach to bring "nature" back into SES analysis. However, rather than speaking in abstract terms,

the paper focuses on the issue of agency—identifying several examples of agency at work. As outlined in the Methods section, the use of non-systematic literature review and of the Socratic method are well suited to the objectives of the paper.

The discussion begins by tracing anthropogenic ecological disturbances and habitat fragmentation as modified evolutionary processes during the so-called "Anthropocene", leading most recently to the emergence and spread of the SARS-CoV-2 virus and COVID-19 disease. Attention then turns to global public health responses to COVID-19, which take place in already disturbed SES. The conclusion highlights how an SES framework can deepen our understanding of the pandemic, and points to the need for a more developed conception of agency regarding the non-human world. Some implications for policy and practice, including public health, particularly in the light of projected future pandemic outbreaks, are provided.

2. Theoretical Framework

The SES framework has sought to analyze the nature of interactions between ecological systems and social "users" and to explain how these interactions "shape" SES. Such systems thinking drew upon the seminal work of Holling that emphasized variability, disturbance, and unpredictability as the underlying rules shaping bio-physical dynamics [1,2]. It was also influenced by theories on the co-evolutionary nature of human and biophysical systems developed by Norgaard [3]. Subsequent elaboration by Berkes and Folke [4,5] placed emphasis on the feedback dynamics between social and ecological systems, seeing human systems as a component of, and in turn shaping, ecological ones.

Most frameworks are modelled upon linear SES dynamics [6]. However, the seminal work of Ostrom moves towards treating social and the ecological dimensions in equal depth [7] (Ostrom 2009). For Ostrom, resources and their users are embedded in complex SES, interacting across scales and levels of organization [7]. Dynamics and complexity are driven by continuous feedback within the system, between resources, actors, and institutions operating at, and across, multiple scales [8]. Ecological subsystems, such as resource systems, interact with users and their governance systems to generate outcomes at systems level [4]. These interactions are governed by rules that structure how individual elements (people, animal species) interact, which, in turn, structures how SES behave at the macro level—that is, whether the system is stable, sustainable, or otherwise. System-level dynamics are often unpredictable, and social factors are often the cause of system disturbances. Social actors, operating in institutional contexts, can also ensure disturbances do not reach a "tipping point", beyond which the system can move chaotically towards new regimes that may even threaten human life. Resilience is not a simple attribute of a system, but the result of social and political choices about how the system is governed and to what ends [9].

Thus, analysis and its related modelling have focused on the response of SES to different forms of perturbations or stressors [8,10]. This has identified properties of SES that shape sensitivity, resistance, or resilience. While systems thinking has been heavily criticized for presenting an underdeveloped view of social change [9,11], the SES approach nevertheless stresses that the capacities and intent of human actors strongly influence the resilience and trajectory of SES [12]. Over time, SES research has largely focused on anthropogenic activities [13], ignoring key, non-human drivers of change [14]. While distinctions made between direct and indirect drivers have helped to address this gap [15,16], human agency has come to be seen as the dominant driver of system disequilibrium [17]. Despite recognition of the dependency of the social world upon the non-human, ecological world within SES scholarship [18], the latter is not well understood or theorized and is predominantly used to warn against system disturbances and the potential societal loss of ecosystem services, such as in tipping point analysis [19]. In addition, SES research has been criticized for drawing too heavily upon the tipping point concept that has its historic roots in mathematics and chemistry, paying little attention to whether the tipping points in a social system are conceptually different than tipping processes in an ecological system and

whether they are driven by the same underlying mechanisms [20]. In short, while ongoing criticism points to the weaknesses in the SES framework when it comes to integrating social science theory, particularly on social change, we argue that, in addition, the framework has ceased to fully take forward earlier theorizing on the dynamics, vibrancy and uncertainty of the ecological component of SES.

In view of this, we argue that the SES framework would be enhanced by engagement with current theorizing that sees "nature" not as secondary to the human world, passive or external [21]. Thus, for example, reaching and going beyond tipping points might be beneficial for some nonhuman entities, a view obscured by overly anthropocentric views within systems thinking. To counteract the tendency to devalue non-human matter and see it as inert and devoid of enchantment or vitality [22], scholars from a range of disciplines are exploring the varied ways in which humans live in what is referred to as a "more-than-human" world [23]. This has led to recognition of how human ideas, social structures, cultures, and economies emerge in relationship to "non-human" agents that possess the potential to shape human possibilities and affect societal change. This reminds us that humans have not been the only sources of historical change, as forces such as earthquakes, floods, volcanic eruptions, and tsunamis are all powerful and sometimes extreme reminders of how non-human forces have shaped social history [24]. However, theorists wish to add to this by advancing a view of agency that recognizes non-human influences that constrain human activity and shape human intentions [25].

The notion of the "agency" of non-humans is central to the multi-disciplinary perspectives of new materialisms and posthumanism [26]. These approaches see all matter as relational and interdependent [27] and decenter a solely anthropocentric focus [28]. The claim has, however, met with skepticisms, since non-humans possess neither the same intentionality nor choices of humans [29]. Classically, humans are distinguished by the ability to convert ideas into purposeful action—a view of personhood that equates agency with the capacity for intentional action [28]. However, conflation of agency with intentionality ignores different kinds of agency [30]. Latour has devised a new theory of agency that recognizes the active role of the nonhumans. He does this by disassociating agency from consciousness, intentionality, and freewill. He sees that these criteria function to distinguish nonhumans from humans and serve render nature passive. To prevent such a human monopoly of agency he proposed that agency is not a given quality but is that which "modifies other actors" through the course of their action, such as in the ways water, weather, or insects can modify others in their environment [31]. Latour [32] maintains that agency is better understood as dispersed among humans and non-humans in what he terms "actor-networks". For Latour, "any thing" that makes a difference to other actors is an agent. Things, which might include microbes, machines, or animals, are not mere backdrop but demonstrate agency when they influence material relations and how history unfolds [32]. In Latour's view, agency is dependent not upon human sovereignty, but on relations with other objects and entities [33]. The work of Bruno Latour and Actor–Network theory has had considerable influence, leading to the recognition of the agency of things and the "entangled" ontologies of subjects and objects. This has illuminated the agency of living non-humans as they impact on societies through "corporeal, geotechnical ... pathological" and a myriad of other processes [34] (p. 912).

In sum, agency, autonomy, and freedom between humans and non-human nature are understood to be different [35], but all are embedded within a larger system of relations. Both forms of agency—human or non-human—while only ever partial, have the power to act within SES [33]. We tease out this understanding of SES dynamics by looking at novel pathogens, focusing on the emergence of SARS-CoV-2 and the spread of the COVID-19 pandemic. We argue that SARS-CoV-2 shows that the non-human is neither external nor merely secondary, but operates in profound tension with the social world, at times dominating outcomes. The theoretical, ethical and policy implications of this view are also addressed.

3. Methods

The research applied an interdisciplinary approach to examine novel pathogens in coupled SES by a team of six researchers coming from different disciplinary backgrounds, including Genetics and Evolutionary Biology, Ecology, Social Geography, Medical Sociology, Philosophy, and Political Science. As an interdisciplinary research group, we agreed to write a scientific paper on our understandings of novel pathogens. The methodological approach emerged during a series of research meetings, held between February 2020 and September 2021, as COVID-19 reached and then maintained pandemic status.

Drawing upon the distinct tradition of qualitative inquiry, the team adopted a non-systematic literature review as one of its key methods, an approach widely used in the Social Sciences and Humanities [36]. Non-systematic reviews require the assessment, critique, and synthesis of existing literature [37]. They do not aim for complete identification and inclusion of all the literature within a specific research field. Rather, they identify relevant papers regardless of specific discipline or methodological framework [38]. Such reviews are recognized as particularly useful when synthesizing complex and heterogeneous evidence, when conducting interdisciplinary literature syntheses [39] and where "formal protocol-driven search strategies may fail to identify important evidence" [39] (p. 1065). The non-systematic literature review was firstly interpretive, in that the literature reviewed was identified as a source of data enabling an emerging set of research questions to be answered [36]. Secondly, it was inductive, where the primary concerns of the review were to develop concepts as well as theories that integrate these concepts [38].

The literature review included searching using keywords within electronic databases across different disciplinary and sub-disciplinary fields, including Critical Health Studies, Environmental Philosophy, Genetics and Evolutionary Biology, Political Ecology, Science and Technology Studies (STS), and Systems Ecology (see Table 1 below). In addition, the review used reference tracking and sources known to the authors [39]. While the review included relevant scientific work published during February 2020–September 2021, it also drew upon the literature that examined previous virus outbreaks (see for example [40,41]).

In addition to the literature review, discussions among the research team utilized the Socratic method, an approach that facilitates reflexive and critical thinking in inter-group dialogue. The method involves engagement with competing views and challenging one's own assumptions about what counts as a good reason. Widely used in educational settings, it allows a comparative judgment that one position is more consistently defensible than available alternatives, so that position can be seen to represent what can meaningfully be said might be true about the world [42]. A series of questions emerged from this dialogue to inform our conceptual framework (see Table 2).

These questions directed the research team in using the Socratic method to build an understanding of the research field, key emerging themes, and to develop their own approach [43]. The process continued until thematic saturation, that is, to the point at which new themes no longer emerge [44].

The following section draws these combined methods to present, first, a discussion of ecological systems, where the links between evolutionary processes and the emergence of novel pathogens are examined; and second, an examination of social processes, through the lens of public health.

Table 1. Key Data Fields: Conceptual foundations, analytic approaches, and keywords used to review literature.

Conceptual Foundations	Analytic Approach	Keywords
Critical Health Studies	One Health; Planetary Health; Public Health; EcoHealth.	Infectious disease; Pandemic; COVID; Human-animal-vector interaction(s); Inequalities; Socio-ecological.
Environmental Philosophy	Ontology; Ethics.	Human-nature relation(s); Ethics of agency; Flattened ontology.
Genetics and Evolutionary Biology	Modified Evolutionary Processes.	Anthropogenic ecological disturbance; Habitat fragmentation; Zoonoses; Novel recombinants.
Political Ecology	Feminist Standpoint Theory; Grounded and Situated Political Ecologies.	Power; Network; Scalar interaction; Human-nature relation; Environmental justice.
Science and Technology Studies (STS)	New Materialisms; Post Humanism.	Humanity's place in nature; Non-human agency; Bioethics.
Systems Ecology	SES; Complexity Theory.	Coupled social-ecological systems; Systems analysis; Disturbance(s); Acts of change; Systems dynamics.

Table 2. Key Questions addressed through interdisciplinary analysis.

Environmental Philosophy
How can we conceptualise the relationship between humans and environment?
How is agency understood?
What are the ethical challenges presented by novel ecosystems and novel recombinants?
If we conceptualise the system as coupled, do humans still have ethical responsibility?
Political Ecology
What does the social response to the pandemic tell us about the distribution of agency and power?
Genetics and Evolutionary Biology
What are the various drivers of novel recombination?
Science Technology Studies
Can humans mitigate the spread and impacts of the new virus within the social world?
What do the measures taken tell us about how humans perceive their agency?
Critical Health Studies
Does a planetary health approach reduce potential risks to further pandemics?
What can be done to improve the approach?
Systems Ecology
How is the link between nature and society theorised?
Can this approach be useful for understanding the pandemic?
Does the SES framework adequately take account of the agency of the non-human world?

4. Discussion

The discussion begins by outlining how human-induced changes have generated novel ecosystems and modified evolutionary processes, which in turn have generated SES feedbacks, such as the novel SARS-CoV-2.

4.1. Modified Evolutionary Trajectories during the Anthropocene

Newly evolved viruses, such as SARS-CoV-2, are emerging under conditions of disturbances within SES. Vulnerability to zoonoses is evidence of feedback within the system, reducing its resilience and making it more likely to shift to an altered state. Although humans have lived alongside, hunted, and been infected by diseases from wild animals since early in their evolutionary history, the domestication of plants and animals is generally regarded as a key anthropogenic activity in the emergence of the most important human infectious diseases [45]. Domestication characterized some of the first SES [46]. Prior to that, it is unlikely that humans would have attained sufficient population density to exert more influence on the landscape than other large mammals. Domestication is thought to have accelerated the process of genetic evolution (through selection and genetic drift) and concomitantly reducing the diversity of genetic resources, particularly in non-wild populations of sheep and pigs [47], but also in other animal populations [48]. Domestication also affects wild species by changing their selective environment, causing them, in turn, to specialize or evolve in other ways. These evolutionary processes can emerge as a response, or feedback to human interventions, such cultural practices, for example the evolution of pests and weeds in response to crop rotations and planting cycles [49].

In evolutionary terms, humans have been influencing the trajectory of the world's biodiversity through population concentration and agricultural practices, including the domestication of animals and plants, for over 11,000 years. However, it is important to distinguish between the recorded history of human beings and their deep history [50]. While historians refer to recorded history, evolutionary processes are also aligned with that of deep history, in which evolution is seen as the combined process of genetic and cultural changes [50]. Overall, by influencing the relative density of wild and domesticated populations and their genetic and species variation, the conditions for rapid pathogen spread and altered (co)evolutionary interactions are set across deep ecological timescales [51]. The co-location of settlements and domesticated animals contributes to the invention and refinement of species categories—domestication is driven by increasing characteristics in animals that produce healthy or resilient stock. These animals also become disease vectors [52]. From an SES framework perspective, the emergence of a novel coronavirus in the human population is but one of numerous examples of how material social practices have led to modified evolutionary processes that, in turn, serve to increase vulnerability in the system.

There are several other key vulnerabilities generated within the system by social practices. As people have colonized previously inaccessible tropical regions, the consequences for the health of colonizers, colonized peoples, and their ecosystems have been significant. Most emergent viruses are zoonotic, with non-domesticated (or wild) animal reservoirs a frequent source [53]. MERS CoV jumped from dromedary camels; SARS is thought to be an animal virus from bats. For SARS-CoV-2, it is thought that the bat acted as reservoir host for its progenitor, potentially the Malayan pangolins (*Manis javanica*) [54], although evolutionary geneticists have not yet agreed on the exact patterns and genomic ancestry of the recombination that produced the virus. While the debate continues, recently a comprehensive phylogenetic re-analysis of SARS-CoV-2 observed that the gene "Spike", the main target for humoral immunity, is found beside a recombination hotspot, which is likely to be driving antigenic shifts in the ancestry of bat Sarbecoviruses [55]. The authors confirmed horseshoe bats, *Rhinolophus*, are the likely SARS-CoV-2 progenitor reservoir species, but a direct proximal ancestor to SARS-CoV-2 is yet to be sampled, with more wildlife sampling needed to pinpoint the exact origins of SARS-CoV-2′s animal progenitor [55]. These results highlight the fact that, although rigorous scientific research can posit hypotheses on the origin of emerging infectious diseases, without comprehensive sampling from candidate wild populations in proximity to expanding agriculture and along the trade chain, it remains both problematic to draw a definitive link between disease outbreaks and their origin and to eliminate alternative explanations.

Deforestation, linked to the expansion of commercial monoculture, has added to the problem of identifying a single cause amongst multiple, dynamic, and complex contributory processes, such as the increased use of biocides and the incursion of artificial chemicals into the environment, causing further disturbances and rendering the system vulnerable to zoonoses. This extends the narrative of COVID-19 beyond the discussion of its starting point, either as associated with the Huanan seafood and wildlife market in Wuhan city, or the laboratory manipulation of a virus that was zoonotic in origin [56]. From an SES framework perspective, the virus is understood as feedback from system disturbances, intensified with the development of urban systems. Wuhan is the largest city in Central China with an urban population of 8.2 million. At the wet market in Wuhan, where the novel coronavirus may have emerged, consumption of wild meat takes place in an urban setting. Urbanization in tropical regions has created new markets for traditionally sourced wild food, potentially damaging biodiversity and creating new public health hazards [57].

The rapid and far-reaching transmission of COVID-19 is also the result of increased connections between places and accelerating, condensed modes of human interaction [58]. Freed from spatial constraints, the compression of space in the globalized world of trade, travel, and transport [59] has provided ideal conditions for pathogen spread. The advent of fast and convenient long-distance travel has significantly increased human movement between places [60]. Migration from sparsely populated areas to urban places has enabled new infectious diseases to spread beyond the boundaries of the ecosystems in which they originated and would have otherwise remained; this was noted during the SARS and Ebola outbreaks [40]. Globalization has meant that disturbances to SES in one place are no longer confined but are experienced across spatial scales. These increased, complex linkages between material and social exchanges, their feedback mechanisms, and the interrelationship between scales have not been adequately accounted for in policy responses. Responses need to distinguish the factors that contributed to the emergence of the virus from those factors that contributed to its spread. Climate change is also a risk multiplier, whereby shifting climate zones have led to the migration of wildlife, resulting in novel inter-species interactions and increased potential for zoonosis [61]. Conflict can amplify the potential for zoonosis, as displaced people flee the terrors of war and retreat into more marginal regions, increasing the potential of encountering a previously unknown virus. The February 2021 outbreak of Ebola around Kivu, in the eastern region of Democratic Republic of Congo, is a known example [62].

Population growth and changing consumption patterns have driven a shift towards industrial agriculture, which is input intensive, relies on high-density livestock production, and results in long commodity-supply chains [63]. Novel multi-species interactions involving dense concentrations of species feature in intensive agriculture. These simplified ecosystems (both structurally and in terms of biological diversity), compared to natural tropical ecosystems or traditional agroecosystems, provide evolutionary opportunities for pathogens, unencumbered by the virus buffering effects of biologically diverse ecosystems. Furthermore, in the past decades, human activities and their indirect effects have shifted "natural ecosystems" outside of their historical range of variability [64,65], resulting in the emergence of novel ecosystems [66]. A novel ecosystem is a unique assemblage of biota and environmental conditions initially resulting from human agency, sufficient to cross an ecological threshold that facilitates a new ecosystem trajectory and inhibits its return to a previous trajectory regardless of additional human intervention [67]. They are the product of mutualistic and coevolutionary processes that are driven by both anthropogenic and non-human agency [68].

In summary, using an SES framework, the COVID-19 pandemic can be seen as the result of feedback loops and cascading interactions within an ecologically and socially disrupted SES [51]. The pandemic results from the convergence of domestication, land use change, and associated practices, such as deforestation, agricultural intensification, and human population growth, where social forces drive disturbances in SES, with cascading effects for human health [69]. However, adopting a perspective that gives weight to

both natural and social processes immerses both biological (genetic) and cultural human processes into a timeframe that takes account of evolutionary and historical scales. This, in turn, enables the disturbances produced by SARS-CoV-2 and COVID-19 to be seen as both the product of human interference and of an ancestral trace. Adding the long durée view is a reminder that social phenomena are not the only occurrences shaping SES dynamics and directs attention to the agency of ecological or non-human nature in shaping evolutionary change [70]. Thus, disturbances to co-evolving SES also demonstrate non-human nature at work. While humans can drive ecosystem change leading to novelty, the emergence of novel pathogens shows that humans are not the only agents shaping the outcomes of these changes. Their emergence challenges claims that one component of our SES (the ecological) has been subsumed into the other (the social world). Rather, the COVID-19 pandemic serves as a sharp reminder of society's limited control over the rest of nature, and that the non-human world operates and engages in profound tension with the social world, sometimes coming to dominate social processes and events.

Furthermore, should the virus prove to be from a laboratory leak, a hypothesis still undergoing scrutiny, as opposed to emerging through encounters along the wildlife trade chain, the arguments about the agency of the non-human world remain. Land use and land cover changes, along with the compression of space and time, as discussed above, open access to key sample sites for researchers, such as bat roosting sites, which can be used for laboratory testing and experimentation. There are profound ethical issues underlying virus manipulation "gain of function" research, including concerns that this may heighten anthropocentric hubris through insufficient attention to the consequences of human action for other life forms. Furthermore, the threat from emerging diseases is partly the result of our success in the "war" against such diseases. Yet, antibiotics that bring control over bacterial attacks on our bodies are in significant measure responsible for human overpopulation; at the same time, dense human populations (urbanization) are perfect media for emerging pandemic diseases [71].

4.2. Pathogens, Pandemics, and Public Health

The previous section traced the evolutionary conditions that triggered the emergence of a novel viral recombinant. This section examines the public health responses to COVID-19, understanding the pandemic against a backdrop of socio-ecological disturbances and in the context of pre-existing socio-material inequalities. Traditionally, public health planning starts with disease as the focus and then analyses the environmental conditions within which it emerged to suppress it. In contrast, SES analysis seeks to understand how diseases are the product of a much wider cycle of disturbances and adaptations within coupled systems. This enables public health issues to be seen as emerging from the complex interplay between humans, animals, and ecosystems [72]. Thus, it is insufficient to allocate resources to the containment of viral outbreaks and spread without understanding the relationships within which both emergence and spread become possible.

The SES framework has been applied to the study of public health to examine a range of empirical issues, including antimicrobial resistance [73], new vector-borne diseases [74], and zoonotic infectious diseases attributed to environmental contaminants [75]. Other approaches have been more theoretical, using the SES framework to develop a deeper understanding of interdependencies between humans and the non-human world. These approaches, include One Health [76], Planetary Health [77,78], EcoHealth [79–81], and posthumanism [82–85]. They understand pathologies at systems level, rather than simply seeing the human or animal as disease vectors [74]. In this way, SES thinking has broadened the scope of public health analysis, developing a "framework for examining how individuals, their health, and their surrounding physical and social environments interact at multiple levels of a health problem and their interdependency" [86] (p. 3). Efforts have focused on understanding the capacity of the social system and public health actions to drive health in the context of SES disturbances, ensuring human health becomes much more complex when these disruptions are zoonotic in origin [75].

With the increase in the frequency and magnitude of novel pathogens originating from wildlife, manifest in a series of outbreaks such as Ebola, H1N1, SARS, and MERS, the convergence of SES framework and public health thinking has advanced [74]. Public health agencies have borrowed from earlier practices of sanitation, regulation of mass groupings, and quarantine, while incorporating insights from recent cases to deal with contemporary threats [74,87,88]. This includes, for example, efforts to limit the global effect of SARS through shifting from highly centralized and fragmented approaches to more coordinated inter-agency approaches operating across scale [89]. In anticipation of future pandemics, national strategies of "pandemic preparedness" have also been developed, setting out plans for feasible interventions into social life and mechanisms for prioritizing techno-biomedical solutions, such as monitoring, contact tracing, treatment, and vaccination [90]. In the current COVID-19 pandemic, collaborations and data sharing demonstrate how the research community can work across traditional silos to develop vaccines and treatment interventions [91]. The production and rollout of the COVID-19 vaccination program is evidence of a well-integrated, multi-layered collaboration between health services, governments, funders, private research institutes, medicine regulators and trial participants that included other-than-human species [92,93].

Despite these advances, perhaps the most significant challenge for the management of a virus emerging at the human, animal, and environment interface is that public health relies on a human-centric view of agency. This approach fails to see viruses as the outcome of relational dynamics. This leads to a reactive, control-centered approach that does little to advance understanding of the wider, ecological context in which diseases emerge and are controlled [74]. The different success level among countries in the Asia-Pacific (based on infection numbers and mortality rates) is directly influenced by institutional, social, and environmental factors, such as trust in government, technology, population density, and past knowledge, as well as traditional public health interventions. This is evident by the contrasting cases of success in Vietnam, New Zealand, and China, on the one hand, and, on the other, the failure of Japan and Korea to control the pandemic in relative terms [94,95].

Furthermore, public health responses to COVID-19 are shaped by pre-existing socio-material and political inequalities, leading to differential vulnerability. The capacity of Singapore, for example, to allocate significant public funds to ease the financial burden of its citizens is an example of the positive impact of a response that arguably enabled citizens to stay at home and comply with government controls [94]. In contrast, poverty is a well-recognized cumulative, pre-existing health risk, which increases the risk of COVID-19 transmission or mortality, reducing the capacity for resilience and recovery [96,97]. In the USA, for example, the economic impacts of pandemic public health measures increased the risk of disease for the most vulnerable communities [98]. Furthermore, COVID-19 patients in poorer communities are most likely to face the brunt of decisions about health care rationing [88,99], although disparities in published data from low- and middle-income countries compared with high-income countries makes them under-represented in assessments of COVID-19 effects [100]. The British Academy [101] Report and Marmot et al. [102] confirm that vulnerable, minority groups in the UK were most affected by pandemic control measures. There are similar findings in India [103], Brazil [104], in prisons [105], in rural communities [106], among children with mental health issues [107], and those in digital poverty [108]. In Uganda, an 82% increase in maternal mortality was related to decreased service utilization because of pandemic measures [109] (Bell et al.). The failure of public health management to take these issues into account undermined recognition of the socio-cultural and economic factors that play a role in promoting resilience of communities [110] and which, in contrast, are given a critical role in the SES framework.

These social and economic vulnerabilities are linked to environmental vulnerabilities and form feedback loops in SES. The global nature of the pandemic brings environmental and social differences to the fore. People in poor housing, for example, often experience the cumulative effects of limited access to green space, and inadequate access to health services [99]. Other environmental disturbances, including endocrine disrupting chemicals

and viral load exposures, make some people more vulnerable to disease compared to others [111]. COVID-19 infection and mortality rates increased, for example, with incidence of obesity, diabetes, cardiovascular diseases, and other chronic disease conditions and was more prevalent in communities who live in poverty, poor housing, and where degraded ambient environments amplify the situation [112]. As COVID-19 disproportionately affected communities with higher rates of exposure to air pollution [113], such disturbances to SES correlated with high disease prevalence and are evidence of the ecological stresses that lies behind the pandemic and its impacts [110]. The burden of this disease remains situated in the Global South, in the BRICS, developing, and least developed countries. This makes it critical to explore how different attributes of the system shape disease outcomes and their consequences. It is also the reason that academics have highlighted the need for a global public health approach that embeds social justice at its core [114] (Ranabhant et al.).

In short, public health responses to the COVID-19 pandemic have been predicated on human agency and its capacity to manage and control, but without due regard for the underlying disturbances in SES that have driven the emergence and spread of the virus in the first instance. Responses based on previous pandemic planning have been reactionary and socially uneven, focusing on dealing with human health needs within an already disturbed SES. Further, they have entrenched pre-existing inequalities that have contributed to disease vulnerability. Accepting that human agency is limited when viewed through the SES framework is not straightforward. It implies considerable scientific and medical uncertainty [115]. It also requires the public health system to treat the pandemic as symptomatic of disturbed SES, rather as a momentary glitch in the system [116].

5. Conclusions

The paper examined the COVID-19 pandemic using an SES framework. It analyzed the pandemic as a product of SES disturbances, adopting an interdisciplinary approach. It found that the literature using the SES framework has come to give undue primacy to social agency in shaping the dynamics of SES. In contrast, the disturbances caused by the novel virus SARS-CoV-2 show the importance of giving more weight to the power of the non-human world in shaping both interactions within SES, and how the system responds to external change. In exploring the agency of non-human nature, the paper brought together the SES framework and posthumanism, the former having its roots in the natural sciences, the latter emerging in the social sciences. Weaving together these disciplinary perspectives, through a new synthesized theoretical lens, brought a shift in the balance away from centralizing the social world to give more weight to the non-human world in shaping how SES work. This focus on non-human agency makes sense when humans are considered as one form of life among others and human history is seen as part of the wider history of life on this planet [50]. This also helps to theoretically situate the biological vulnerability of humans in the face of the COVID-19 pandemic. Recent developments in SES thinking, in both public health and evolutionary biology, also confirm the need for pandemic responses to start from a more integrated understanding of human-nature systems.

Examining the agency of the non-human world also contributes to clarifying and extending understanding of "nature" itself. Several forms of the non-human world have come to the fore here, including the relational aspect as embedded within a coupled system of material relations, and which we find in the classic SES literature; the natural/biological element, that was stressed in Latour's work, and which finds expression in the emergence of SARS-CoV-2; and the process of the genome novel recombinant, which is aligned with the conceptualization of the non-human as vibrant.

While acknowledging agency across SES, that is, between the human and non-human worlds, this paper does not propose a flattened ontology, wherein humans cease to retain responsibility. Instead, recognizing different forms of agency, humans remain ethically implicated in the causes of, and feedback responses to, ecological disturbances. Thus, alongside existing efforts to identify the key characteristics of the social system that are needed to ensure responses to system perturbance promote resilience, attention also needs

to turn to our role as moral agents [114]. The recognition that humans cannot control non-human agency may come across as a limitation to the SES framework. However, the approach proposed here enables a focus on the outcomes over which humans have agency, such as socio-economic inequities and land and resource degradation. How the way forward is navigated is more than a governance issue, favoring better and more timely policies aimed at returning to the status quo. Instead, we point to the need to take account of the living world by developing an *ethics of interdependency* to better promote SES resilience.

These conclusions have implications for practice. To avert future pandemics, public health policy and practice must shift from a strategy of "preparedness" and disease control to one that involves recognizing complex relations beyond the social realm and takes account of the factors that shape the overall health of SES [89]. In a global context, public health adaptation and management strategies need to give greater cognizance to the unequal distribution of disease burdens, where matters of justice, and thus our moral responsibility, come sharply to the fore. They also require new approaches that regard disease as an indication of disturbances in, and vulnerability of, the overall SES. This calls for the development of new public health models and methods to monitor SES health and resilience, while also assessing the health responses and social learning required when SES are threatened [117]. A better understanding of the coupled interactions between social and ecological systems is crucial for sustainability, and its governance. Such efforts need to be accompanied by a questioning of the idea that society can master SES and that the non-human world exists merely to support humans and their health. Short term and emergency policy responses to the pandemic could begin to address the complex feedback mechanism that led to the rapid global spread of COVID-19. This paper highlights the importance of the longer-term policy changes that are needed to halt the emergence of future virus by reversing the degradation of natural resources and enabling ecological recovery.

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