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Discussion

The ecosyndemic framework of the global environmental change and the COVID-19 pandemic

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ABSTRACT

The ecosyndemic theory combines the concept of ‘synergy’ with ‘epidemic’ and the term “eco” implies the role of the environmental changes. Each of the conditions enhances the negative impacts of the other in an additive way making our society more vulnerable and heightening individual risk factors. In this study, we analyze the mutually reinforcing links between the environment and health from the complexity angle of the ecosyndemic theory and propose the characterization of the COVID-19 pandemic as ecosyndemic. We use the term ‘ecosyndemic’ because the global environmental change contributes to local-scale, regional-scale and global-scale alterations of the Earth’s systems. These changes have their root causes in the way that people interact with the physical, chemical, and biotic factors of the environment. These interactions disturb nature and the consequences have feedbacks in every living organism.

1. Introduction

The planet’s ecological and climate systems are interconnected by numerous interactions (Schimel, 2013). Earth’s climate is an integral component of ecosystem functioning and human health is influenced directly and indirectly by the effects of atmospheric conditions upon terrestrial and marine ecosystems. Elements of biodiversity (genes, species, and ecosystems) are directly influenced by weather conditions and climate variability. Climate change influences ecosystems through changes in precipitation, atmospheric carbon dioxide concentration, water balance, ocean chemistry, and the frequency and magnitude of extreme weather events (Malhi et al., 2020).

Ecosystems are also being threatened by human activities such as deforestation, agriculture intensification, excessive resource extraction, habitat degradation and fragmentation. The ecological footprint of human activities has transformed the earth’s natural systems and is altering the planet’s land cover, rivers and oceans, climate system and geochemical cycles.
The human impacts on biodiversity are contributing to the conditions for the transmission of pathogens between animals and humans (known as zoonoses) (Borzée et al., 2020).

Epstein et al. (2003) stated that waves of infections often accompany periods of social and environmental transition. An outbreak of an old disease or the emergence of a new one may result from changes in the epidemiology of agents, the ecology of agents and vectors, the environment, or a combination of these (Epstein, 1992). Such changes may initiate alterations in several of these components, creating the conditions for widespread epidemics that may become pandemics. Morens and Fauci (2020) point out that newly emerging and re-emerging infectious diseases have been threatening mankind since human hunter-gatherers first settled into villages, domesticated animals, and cultivated crops. The domestication of animals and plants is a key turning point in human history which represents a structural and extensive manipulation of nature. Importantly, human hunter-gatherers did not establish permanent settlements but they changed their food habits and lifestyle and began to domesticate animals during a time of climatic transition that followed the Last Glacial Maximum (Beck 2004; McHugo et al., 2019). On the other hand, the domestication of animals triggered spillovers of animal microorganisms (Epstein et al., 2003). In particular, the linear relationship between the time that the animal domestication started (about 12,000–15,000 years ago) and the number of shared pathogens with humans showed that the earliest domesticated animals, such as dogs, cattle, sheep, goat and pigs share the most diseases with humans (Perrin et al., 2010; Morand et al., 2014). Studies on the ecology of zoonoses (Karesh et al., 2012; Jelinek et al., 2021) conclude that the recent and historical emergence of zoonoses can be considered as the endpoint in a sequence of events involving viral evolution and ecology. The ecology of the virus and the ecology of the host(s) can create the potential for zoonotic transmission. Human actions such as land-use changes, deforestation, natural resources extraction, animal production systems, modern transportation, global trade and antimicrobial drug use can provide animal to human transmission opportunities (Karesh et al., 2012; Gibb et al., 2020; Jelinek et al., 2021). Importantly, the domestication of animals, farming and grazing of livestock, and hunting of wild animals increase the contact of people with animals and provide transmission opportunities (Karesh et al., 2012; Spernovasilis et al., 2022). Based on Jelinek et al. (2021) the viral transmission to humans may occur through the consumption of wild-caught animals which are the reservoir species of pathogens but also the simple proximity to the host species could be sufficient for the transmission, as in the cases of both SARS-CoV-1 and SARS-CoV-2.

Besides human activities, environmental problems and global climate change are contributing to the emergence of diseases that afflict humans. As the climate becomes more unstable, its role increases, such as in vector-borne and rodent-borne diseases (Epstein et al., 1998). A warming and unstable climate is playing an ever-increasing role in driving the global emergence, resurgence and redistribution of infectious diseases (McMichael et al., 1996; Epstein, 2001).

Previous studies have underlined the critical role of climate change in the emergence of SARS-CoV-2 and the spread of COVID-19 globally (Yan Yam, 2020; Lorentzen et al., 2020; Beyer et al., 2021; Gorji and Gorji, 2021; Joshi et al., 2021; Ebi et al., 2021; Rodó et al., 2021). McNeely (2021) appraised the environmental dimensions of the ongoing pandemic and stressed that COVID-19 provides an opportunity to confront the issues of human health, climate change and biodiversity loss with an integrated and holistic approach supporting the One Health concept. Many authors including Maipa et al. (2021) and Spernovasilis et al. (2022) support the One Health perspective for coordinate, interdisciplinary and sustained response to address the threats that emerging diseases and COVID-19 pose to human. The ongoing pandemic serves as a stark reminder of the strong and dependent relationship between people and nature, demonstrating the consequential impacts of the loss and degradation of biodiversity which increases the risk of disease transmission from wildlife to people.

In this paper we highlight the links among climate, ecosystems and infectious diseases, in order to interrelate the complex and multi-layered processes which affect the outbreak and global spread of the COVID-19 pandemic. We reviewed the literature about the human-ecosystem interactions that contribute to the emergence of infectious diseases and we provide evidence about the links between the current pandemic and the environmental factors, highlighting the need for an holistic approach in order to study the COVID-19 from the origin of SARS-CoV-2 to the spread of the disease worldwide. Also, we provide recommendations for environmental policy to build resilience against the global environmental change and strengthen our societies for the current and future pandemic. Overall, we place emphasis on the critical analysis of the literature focused on the characterization of COVID-19 as a ‘syndemic’ and propose the eco-syndemic approach as a useful tool to study the complex connections between the climate change and COVID-19 because the pandemic is taking place against the backdrop of the environmental crisis.

2. Background: climate change and health

The World Health Organization (WHO) has stated that “Climate change is the greatest challenge of the 21st century, threatening all aspects of the society in which we live”. Overwhelming evidence shows that climate change is a menace to societies. The trends of global climate change have been accelerating over the last few decades and it has become increasingly apparent that human actions are changing atmospheric composition, thereby causing global environmental changes notably through the release of greenhouse gases. According to the World Meteorological Organization (WMO, 2019) the years 2015 to 2019 were the five warmest on record. The average global temperature for 2015–2019 was 1.1 °C ± 0.1 °C warmer than pre-industrial period (1850–1900) and is the warmest of any equivalent period on record. Also, the 5-year period 2015–2019 is 0.21 °C ± 0.08 °C warmer than the average for the previous 5-year period 2011–2015. The year 2016 is the warmest on record, beginning with an exceptionally strong El Niño event, a phenomenon which contributes to elevated global temperatures (WMO, 2020). Notably, the 5-year average temperatures were the highest on record for large areas of the United States including Alaska, eastern parts of South America, most of Europe and the Middle East, northern Eurasia, Australia, and areas of southern and eastern Africa (WMO, 2019).

The global mean sea-surface temperature for the 5-year period 2015–2019 was approximately 0.83 °C above the pre-industrial levels and 0.13 °C warmer than the average for the 2011–2015 period (WMO, 2019). Most of the areas over the oceans were warmer than average, but below-average sea-surface temperatures were observed to the south of Greenland, one of the few areas globally to have seen long-term cooling. As for precipitation, a comparison of the difference in monthly average precipitation totals between (2015–2019) and (2011–2015) shows that many regions had higher precipitation in the latter period than in the former and vice versa (Fig. 1) (WMO, 2019).

In addition, the Arctic ecosystems and communities are increasingly experiencing continued warming and declining arctic sea ice cover, continued ice mass loss in the glaciers and the Greenland and Antarctic ice sheets, and a clear downward trend in the northern hemisphere spring snow cover. Furthermore, many of the major impacts of climate change are associated with extreme weather events and natural disasters like tropical cyclones, storms, tornadoes, floods, droughts, wildfires, extreme heat and cold events, and heavy snowfalls. Heat waves were the most fatal meteorological hazard during the 2015–2019 period, affecting all continents and resulting in new temperature records in many countries. For instance, extreme heat waves hit Western Europe in June and July 2019, breaking historical temperature records in France, Switzerland, Austria, Germany, the Czech Republic, Italy and Spain. In France, 1435 excess heat-related deaths were reported during the heat waves. WMO (2020) reported that the year 2020 was one of the three warmest years on record despite neutral conditions of El Niño early in 2020 and La Niña conditions which has been developed since late August 2020 (Box 1).

The above-mentioned increase in global average temperature is associated with significant changes in the worldwide weather patterns. Even a 1 °C change in global temperature is significant because it takes a vast amount
of heat to warm all the oceans, atmosphere, and land by that much. Historically, an approximately 1 °C decrease in global temperature was all it took to plunge the Earth into the Little Ice Age. This was a time of modest cooling of the Northern Hemisphere, with temperatures dropping by about 0.6 °C and dramatic glacial advances during the 15th – 19th centuries. The multi-centennial perturbations during the Little Ice Age were associated with natural causes such as the injection of sunlight-reflecting sulphate aerosols by explosive volcanic eruptions and a prolonged period of reduced solar activity from about 1645 to 1715, known as the Maunder Minimum (Mann, 2002). The widespread reports of famine, disease, and increased child mortality in Europe during the 17th–19th century are partly related to colder conditions combined with altered patterns of atmospheric circulation and associated weather conditions (Mann, 2002). “A vicious cycle had started: Diseases claimed the lives of millions, leaving extensive land to reforest, lowering the levels of carbon dioxide (CO2) with a subsequent decrease in temperature” (El Hamichi et al., 2020). On a global scale, extreme climate with freezing conditions increased harvest failures, famine, and malnutrition, resulting in prominent outbreaks of new and old epidemics (McMichael, 2012; El Hamichi et al., 2020). The climatic variability during the period of the Little Ice Age may have led to the outbreaks of plague during the Medieval period (Epstein, 2019; Campbell Bruce and Ludlow, 2020). Zhang et al. (2011) investigated the causal mechanisms between climate change and human crisis between the years 1500 and 1800 based on historical data including Northern Hemisphere and Europe temperature anomalies, the grain yield and price, agriculture production, famine years and the number of plagues. Their study covers the period of Little Ice Age and the crisis of the 17th century concluding that the variability of climate triggered a chain of bio-productivity, socioeconomic, demographic problems and the plagues epidemics (Zhang et al., 2011). With reference to this study, McMichael (2012) points out that during the Little Ice Age the additional cooling of 0.2 °C during the coldest part of the 17th century was accompanied by harvest decline, famine and outbreaks of plague.

Box 1
El Niño-Southern Oscillation.

The El Niño/Southern Oscillation (ENSO) is a naturally occurring phenomenon in the central and eastern equatorial Pacific Ocean, which comprises three phases: El Niño, La Niña and Neutral. El Niño and La Niña, which are the opposite phases within the ENSO cycle, are the oceanic components and the Southern Oscillation is the atmospheric counterpart of the ENSO. El Niño events (warm events) begin with large-scale warming of surface water in the central and eastern equatorial Pacific Ocean and La Niña events (cold events) are associated with large-scale cooling of the ocean surface temperatures in the same region in the equatorial Pacific. These changes in ocean temperature patterns during El Niño and La Niña are accompanied by atmospheric pressure changes known as the Southern Oscillation, which is an east–west see-saw-like movement of air masses between the Pacific and the Indo-Australian areas (WMO, 2014). These events are associated with significant impacts on regional climate through their influence on large scale weather circulation patterns, which in turn, influence Earth’s ecosystems.

During the Little Ice Age, the extremely low temperatures and the prolonged winters conditions led to widespread crop failure. The snow cover that lasted until spring delayed the growing of the plants and led to a late...
harvest. The frost periods in April and May caused losses in the grain production, as well as the snow-mold lowered the yield of grain (Camenisch and Rohr, 2018). In western and central Europe the most devastating impacts on agriculture were the long wet spells during the harvest period because the continuing rainfall could reduce the nutrient contents of the soil (Pfister and Brázdzil, 2006; Camenisch and Rohr, 2018). Moreover, losses in stored grain were caused by insects and fungi (Pfister and Brázdzil, 2006). The food shortages led to higher food prices and a great socioeconomic crisis (Pfister and Brázdzil, 2006; Zhang et al., 2011).

Under the influence of these adverse environmental and social circumstances, the advent of a plague was not a coincidence. Both harvest losses and the plague pandemic arose from common environmental disturbances which were caused by the harsh climatic conditions around the Northern Hemisphere (Campbell, 2018). The Black Death (also known as the Plague) was a bubonic plague pandemic occurring in Afro-Eurasia from 1346 to 1353 caused by the bacterium Y. pestis. Studies have showed that environmental factors such as sudden changes in temperature and precipitation and natural disasters have an impact on Y. pestis host ecologies that can cause outbreaks in human populations (Spyrou et al., 2022). Based on the literature, the Qinghai-Tibet plateau in Western China (Campbell, 2018) or the Tian Shan region (Spyrou et al., 2022) are the most likely reservoir regions for human plague in the Medieval period, while the movement of people across the “Silk Road” seems to have spread the plague (Campbell, 2018).

The above research shows that climate change poses many challenges to human health and well-being, though it is just one of the several concurrent environmental changes that simultaneously and interactively affect human health.

Climate change accompanied by an increased frequency and intensity of heat waves will provoke elevated daytime and night-time temperatures which in turn will result in heat-related illness and deaths such as heat exhaustion and heatstroke (Rocque et al., 2021). The excess mortality from heat waves is related to cardiovascular, cerebrovascular, and respiratory disease and is concentrated in susceptible people, especially the elderly and individuals with pre-existing illness (Haines and Patz, 2004; Rocque et al., 2021). Moreover, rising of sea levels, heavier and extreme precipitation and more intense tropical cyclones contaminate water and increase disease flow from flooding, and lead to increased risk of water-borne diseases such as gastrointestinal diseases (e.g., diarrhea and cholera) and may provoke physical health problems (e.g., injuries) and malnutrition (Lee et al., 2020; Rocque et al., 2021).

Generally, climate is a key determinant of health and constrains the range of infectious diseases, while weather affects the timing and intensity of outbreaks (Epstein, 2001). Therefore, climate change can exacerbate existing health threats or create new public health challenges through a variety of pathways. Climatic factors influence the emergence and re-emergence of infectious diseases, in addition to multiple human, biological, and ecological impacts. Infectious disease agents such as viruses and bacteria, and vectors such as mosquitoes, are influenced by seasonality and changes in temperature, rainfall and humidity. Climate change can cause shifts in host and vector ranges, alter life cycles of vectors and hosts, affect migration of people and domestic animals, increase the susceptibility of animals to disease, increase in the range or abundance of vectors and animal reservoirs and prolonging the transmission cycles of vectors (McNeely and Mainka, 2006).

In short, these changes in climate can favour the transmission of climate-sensitive diseases, such as vector-borne and rodent-borne diseases, by affecting the ecology of the diseases, their distribution, and the number of disease cases.

3. Infectious disease in an era of global environmental change

In the last four decades, a great proportion of pathogen emergence into human populations have been linked with wild or domestic animal reservoirs (Perrin et al., 2010; Karesh et al., 2012; Morand et al., 2014; Jelínek et al., 2021). Pathogens can be transmitted from animals to humans (zoonosis) and from humans to animals or through anthroponosis, a process refers to as “reverse” zoonosis (Beirne, 2021). Pathogens can also be transmitted in bidirectional or multidirectional routes either from animal to human to animal, or from human to animal to human.

As for SARS-CoV-2, its origin and routes of transmission have been widely investigated in the scientific literature (Domingo, 2021; Holmes et al., 2021; Lytras et al., 2022; Pekar et al., 2022; Worobey et al., 2022). The zoonotic origin of SARS-CoV-2 has been already suggested in January 2020 (Domingo, 2021). Since then several studies have supported this statement providing evidence and linking its origin with the ‘wet’ markets where non-domesticated wild animals, either captive-bred or wild-caught, dead or alive, are available for purchase (Domingo, 2021; Holmes et al., 2021; Lytras et al., 2022; Pekar et al., 2022; Worobey et al., 2022). The Huanan market (Huanan Wholesale Seafood Market) was an early and major epicenter of SARS-CoV-2 infection, where the majority of cases of the first hospitalized patients with pneumonia of unknown etiology (later named COVID-19) had direct exposure (Holmes et al., 2021; Lytras et al., 2022; Worobey et al., 2022). Based on these studies the potential source of virus transmission into the human population in the first cases was from infected live mammals sold at the Huanan market. It has been reported that seafood, poultry, and a variety of live captive wild animals or farmed mammal species were sold at Huanan market (Xiao et al., 2021). The species on sale include mammals such as civets and raccoon dogs, birds and reptiles which were sold alive, caged, stacked and in poor condition (Xiao et al., 2021).

The SARS-CoV that have caused the outbreak of SARS in 2002–2003 have been associated with wet markets selling live animals and involved species (e.g. palm civets and raccoon dogs) while it has been proposed that the bats (genus Rhinolophus) are its natural reservoirs (Wang and Eaton, 2007). Both SARS-CoV-2 and SARS-CoV are members of the species Severe Acute Respiratory Syndrome-related Coronavirus that forms the sole member of the Sarbecovirus subgenus of Betacoronaviruses, a group of viruses which have been found in horseshoe bats (family Rhinolophidae) (Lytras et al., 2022). As for SARS-CoV-2, Lytras et al. (2022) performed a phylogenetic study on SARS-CoV-2 and the related bat and pangolin sarbecoviruses and concluded that horseshoe bats (genus Rhinolophus) are the likely reservoir species for the SARS-CoV-2 progenitor.

Also, it is known that coronaviruses infect a variety of avian and mammalian species. Seven human coronaviruses (HCoVs) (HCoV-229E, HCoV-NL63, HCoV-OC43, HCoV-HKU1, MERS-CoV, SARS-CoV, SARS-CoV-2) are known to infect humans. Four of these (HCoV-229E, HCoV-OC43, HCoV-NL63 and HCoV-HKU1) are responsible for 15–30 % of common cold in humans infecting all ages and peak during winter months in temperate climates (Coerd and Khachemoune, 2021).

On a global scale, the origins of emerging infectious diseases and specifically the emergence of new zoonoses are often linked with anthropogenic environmental factors, including land-use change, human demographic changes (especially migration and increase in population density) and climate changes that have resulted in increased frequency of wildlife-livestock-human interactions especially in tropical and subtropical regions rich in diversity of vertebrate species and their microbes (CBD, 2020). These global changes increase the risk of repeated spillover of microbes from wildlife to people, and may explain why most emerging infectious diseases and almost all pandemics have been caused by zoonoses (CBD, 2020). The total number of outbreaks of diseases has increased globally since 1980 (Smith et al., 2014). Examples of infectious diseases emerging during the past few decades include HIV/AIDS, SARS, MERS, swine flu (H1N1), H5N1 influenza, avian influenza A (H7N9), Nipah Virus infection, and Ebola virus disease as well as COVID-19 and monkeypox (Morens and Fauci, 2020; Gebreyes et al., 2014; Baker et al., 2022).

Nowadays, 60 % of all human pathogens originate from animals and approximately 75 % of the newly emerging infectious diseases are zoonoses (Perrin et al., 2010; Karesh et al., 2012; Gebreyes et al., 2014; Leal Filho et al., 2022). Based on Gebreyes et al. (2014) the emergence and re-emergence of infectious diseases are driven by various factors including genetic, biological, socioeconomic, anthropogenic, demographic and
environmental factors, urbanization-urban migration, population density, ecosystem changes and the climate change. Therefore, these changes are significant drivers in the emergence, distribution, and transmission of numerous infectious diseases and illustrate clear links between epidemics, pandemics and biodiversity. Epidemic refers to an increase, often sudden, in the number of cases of a disease above what is normally expected in that population in that area, while pandemic refers to an epidemic that has spread over several countries or continents, usually affecting a large number of people (Dicker et al., 2006).

Baker et al. (2022) analyzed the human connectivity with infectious disease outbreaks, between the years 1970 and 2020, based on the trends of urban population growth, international air travel and trade in association with the deaths from the major epidemics (e.g., SARS, Ebola virus disease, COVID-19). They concluded that recent global changes have increased the risk of infectious disease outbreaks in multiple ways. For example, climatic changes affect the geographical range of vectors and reservoir species, while population growth increases the contact with reservoir species (Baker et al., 2022).

Casadevall (2020) focuses on another threat resulting from climate change and especially global warming: “the strong possibility that new, previously unknown infectious diseases will emerge from warmer climates as microbes adapt to higher global temperatures that can defeat our ‘endothermy thermal barrier’”. Humans have an immune system that defends us against microorganisms that can cause infections. One of its mechanisms is the maintenance of the endothermy thermal barrier, which is mainly controlled by a region in the brain called the hypothalamus, regulating the human body temperature within its normal values.

4. Human-ecosystem interactions contribute in the emergence and re-emergence of infectious diseases

The infectious diseases have emerged worldwide over the past few decades (Box 2). In addition, vector-borne diseases such as malaria, yellow fever, and dengue fever, have spread due to climate change that affects the transmission dynamics and geographic spread of their vectors and can alter the ecosystems in which vectors may thrive or fail when a suitable climate is necessary for the persistence or emergence of a vector-borne disease (Rocklov and Dubrow, 2020).

Environmental factors may have indirectly increased the risk for Sin Nombre virus (SNV) in the Four Corners region (Arizona, New Mexico, Colorado, Utah) of the United States in 1993 (Engelthaler et al., 1999). The dramatic increase in precipitation pattern during the 1992–1993 El Niño phenomenon resulted in an abundance of rodent food resources (e.g., vegetation and insects) and a 20-fold rodent population increase over the previous year at the Sevilleta National Wildlife Refuge in central New Mexico, which in turn resulted in the 1993 outbreak of HPS (Hantavirus Pulmonary Syndrome) in the Four Corners region.

Also, Ebola virus disease (EVD) outbreaks in Africa are linked to the increased contact of humans with wildlife due to extensive deforestation, hunting and mining (Rugrarabamu et al., 2020). EVD outbreaks since 1976 have been occurring in the ‘Ebola Forest Belt’ which stretches across West and Central Africa (Meseko et al., 2015), where forest ecotypes provide habitats for diverse fauna. Alterations to the natural ecosystem from clearing of forests for agricultural intensification and livestock grazing purposes or rural urbanization have increased proximity between the human population and wildlife, leading to enhanced contacts with Ebola virus-carrying natural hosts (Rugrarabamu et al., 2020).

The first Nipah virus (NiV) outbreak in Malaysia in 1998 has been linked with the oil palm plantations that have replaced the tropical forest habitat of Malaysia’s fruit bats (of the family Pteropodidae). The close proximity of commercial pig farms to fruit trees in Malaysia created an environment where the pigs fed on fallen fruit contaminated with excreta from the bats, which are the reservoir host of Nipah virus (McNeely, 2021). A combination of events in Malaysia contributed to the outbreak of Nipah virus disease, including the 1997–1998 slash-and-burn deforestation in Indonesia which was exacerbated by a drought driven by the strong 1997–1998 El Niño event, which had major impacts in many regions around the world. The equatorial Asia-Pacific region experienced significantly reduced rainfall over an extended period in many areas with destructive consequences in the environment and decreased agricultural production affected by regional drought (WMO, 1999). These events led to the reduction in the availability of flowering and fruiting forest trees for foraging by the bats (Chua, 2003).

Since early May 2022, monkeypox virus (MPXV) has re-emerged and multiple cases were identified in several non-endemic countries in Europe, U.S.A., and Asia (Gong et al., 2022). MPXV was first identified in humans in 1970 in the Democratic Republic of the Congo and most cases have been reported from rural, rainforest regions Central and West Africa (https://www.who.int/news-room/fact-sheets/detail/monkeypox). A study conducted by Thomassen et al. (2013) indicated that forest clearing and climatic factors are significant driving factors of the transmission of MPXV from wildlife to human under current climate conditions. Also, they indicated projecting shifts in the geographic distribution of human MPX under climate change where environmental conditions may become more suitable its transmission (Thomassen et al., 2013). Based on the literature, the expansion of the rainforest driven by warmer and more humid condition may allow MPXV and its reservoirs to expand their geographic range, as well as the deforestation and flooding could increase habitats for species carrying MPXV (Brown and Leggat, 2016). In accordance with Froment et al. (2010) monkeypox cases have been recorded in Unity State, Sudan after severe flooding. This introduces the hypothesis that floods decrease the habitat availability for terrestrial mammals and facilitated the possible contact between potential animal reservoirs and humans (Froment et al., 2010).

5. COVID-19 emergence: linkages among human-ecosystem interactions, environment, weather, air pollution and climate change

During the early stages of the COVID-19 pandemic a cool and dry environment in a mesothermal climate may have favoured the spread of SARS-CoV-2 (Gutiérrez-Hernández and García, 2021). Although this could reflect a climate sensitivity, could also reflect global trade and travel and

| Name of disease                  | Year of emergence | Region of emergence         |
|---------------------------------|-------------------|-----------------------------|
| Zika virus disease              | 1947              | Uganda, Africa              |
| Chikungunya                    | 1952              | Tanzania, Africa           |
| Monkeypox                      | 1970              | Democratic Republic of Congo, Africa |
| Lyme disease                    | 1975              | USA                         |
| Ebola virus disease (EVD)       | 1976              | Democratic Republic of Congo, Africa |
| HIV/AIDS                        | 1981              | USA                         |
| Hantavirus Pulmonary Syndrome (HPS) | 1993           | Latin America               |
| HSN1 influenza                  | 1997              | China                       |
| Nipah virus disease             | 1999              | Malaysia                    |
| Severe Acute Respiratory Syndrome (SARS) | 2003          | Asia                        |
| Swine flu (H1N1)                | 2009              | Mexico                      |
| Middle East Respiratory Syndrome (MERS) | 2012       | Saudi Arabia                |
| Avian influenza A (H7N9)        | 2013              | China                       |
| Coronavirus disease (COVID-19)  | 2019              | China                       |

Sources: CDC (https://www.cdc.gov/) and WHO (https://www.who.int/).
international tourism. However, if environmental variables do influence the trajectory of the pandemic, the seasonal progression of the disease will lead to different implications across the globe, varying by hemisphere, region, and climatic zone (Smit et al., 2020). Nonetheless, cases and deaths of COVID-19 have been reported in every continent, apart from Antarctica, during the first months of the pandemic. Antarctica was one of the last regions of the world affected directly by the pandemic due to its remoteness and sparse population; its first cases of COVID-19 were reported on 21 December 2020.

Researchers have investigated the association of SARS-CoV-2 transmission and COVID-19 spread, with meteorological and environmental factors such as the air temperature, relative humidity, wind speed, precipitation and ultraviolet (UV) (Dobricic et al., 2020; Sanchez-Lorenzo et al., 2021; WMO, 2021; D’Amico et al., 2022; Pramanik et al., 2022; de la Fuente et al., 2022; Valsamatsi-Panagiottou and Penchovsky, 2022; D. Wang et al., 2022; X. Wang et al., 2022). For instance, Sanchez-Lorenzo et al. (2021) claimed that the atmospheric circulation pattern in February 2020 contributed to shape the spatial pattern of the outbreak of COVID-19 during the first stages of the pandemic in Europe before the implementation of public health strategies. In general, cold and dry weather conditions aggravate the transmission of the virus because human resistance to infectious diseases becomes weaker (D. Wang et al., 2022; X. Wang et al., 2022).

D’Amico et al. (2022) studied the mortality and vaccination rates during the first year of COVID-19 pandemic in both Europe and the U.S. only in temperate climate countries that defined as the countries with mean temperature is above −3 °C and below 18 °C in the coldest month. They found that COVID-19-related deaths decreased during the summer period and the effect of vaccination rates on mortality was stronger when temperatures were lower. Pramanik et al. (2022) in order to understand the regional differences of COVID-19 analyzed data from 228 cities around the world, into tropical, subtropical and temperate zones. They found that in the tropical regions such as India and Brazil, the mean diurnal temperature range and temperature seasonality significantly predict the infection outbreak (Pramanik et al., 2022).

During February 2020, the main atmospheric circulation pattern was characterized by an anomalous anticyclonic system over the western Mediterranean basin, centered between Spain and Italy, and lower pressures over northern Europe centered over the Northern Sea and Iceland. This atmospheric circulation represents the North Atlantic Oscillation (NAO) in its positive phase, which reflects below-normal heights and pressure across the high latitudes of the North Atlantic and above-normal heights and pressure over the central North Atlantic, the eastern United States and western Europe. These support mild, stormy and wet winter conditions in northern Europe and eastern US, while northern Canada, Greenland and southern Europe are prone to cold and dry winter conditions. In the context of global climate change, the anthropogenic forcing may also alter the characteristics of the NAO itself (Deser et al., 2017).

Epidemiological studies of COVID-19 that have investigated the relationship between air pollution and COVID-19 incidence and mortality rates have found that the chronic or short-term exposure to air pollution may make people more susceptible to SARS-CoV-2 infection and exacerbate the symptoms of COVID-19 (Urrutia-Pereira et al., 2020; WMO, 2021; de la Fuente et al., 2022; Yates et al., 2022).

The airborne transmission of SARS-CoV-2 from human-to-human through respiratory droplets and aerosols has been demonstrated, while the risk of contagion with the virus could be minimized at human-to-human distance, about 1.5 m to 2 m (Valsamatsi-Panagiottou and Penchovsky, 2022). Therefore, the potential role of air pollutants in the spreading of COVID-19 is plausible. For instance, Particulate Matter (PM) could act as a “carrier” for the virus influencing its persistence in the air and facilitating its transport to longer distances (Rizzo, 2022). Furthermore, air pollution exposure increases human host susceptibility to respiratory viral infections by disrupting the body’s ability to fight off infections (Aykaç and Etiler, 2022).

Currently, there is a growing amount of research in the scientific literature concerning the continuously evolving SARS-CoV-2 variants that have been identified so far, including Alpha, Beta, Gamma, Delta and Omicron variants (Wang and Han, 2022). Based on Wang and Han (2022) there are knowledge gaps concerning the environmental transmission routes of the variants. As for the transmissibility of Delta variant (B.1.617.2) there is strong evidence that it is much higher than the original SARS-CoV-2. In addition, Omicron variant (B.1.1.529) has a high number of mutations in the spike protein that has a large impact on the virulence of SARS-CoV-2 and transmissibility contributing to increased immune evasion and high risks of re-infection (Boeger et al., 2022). As for the origin of Omicron strain there are speculations due to its unusual mutations and its super spreading events by this variant (Boeger et al., 2022). For instance, Monajemi et al. (2023) consider that the rainy, humid and warm climate in the Amazon rainforests a suitable substrate for emerging any further variants of the coronavirus. Boeger et al. (2022) support that the anthropogenic opportunities facilitating the colonization of the virus among non-human mammals, some of which became hosts for the spreading of virus in mammalian hosts, including humans. The humans are considered as ‘ecological superspreaders’ because their mobility patterns and activities pose risks for the emergence of new variants of the virus (Boeger et al., 2022).

In addition, climate change could have played a direct role in the emergence of SARS-CoV-2, and the COVID-19 pandemic. Beyer et al. (2021) reported large-scale changes in the type of vegetation in the southern Chinese province of Yunnan, and adjacent regions in Myanmar and Laos, over the past century. Climatic changes characterized by higher atmospheric CO2 levels affected this region by increasing temperature, altering precipitation patterns, and decreasing cloud cover, affecting the growth of plants and trees so natural habitats changed from tropical shrubland to tropical savannah and deciduous woodland. Climate change over the past century has given southern Yunnan Province suitable habitat for many bat species, and it is now considered a global hotspot for studying the climate change-driven increase in bat species richness and coincides with the likely spatial origin of bat-borne sources of SARS-CoV-1 and SARS-CoV-2 (Beyer et al., 2021).

Moreover, climate change, global warming and natural phenomena (e.g., forest fires, volcanic eruptions, cyclones, tornadoes and floods) impact human health, changing susceptibility to infections, the distribution of reservoirs, carriers, and their exposure to a wider range of host population (Rodó et al., 2021; Gupta et al., 2021). Historically, infectious diseases outbreaks are often related to extreme weather events such as floods and droughts (FAO and UNCCD, 2021; Mora et al., 2022). Coincidentally, East China and regions of Yangtze River suffered from a severe drought in autumn 2019 following the high temperatures and low rainfall from August 2019 to October 2019 causing widespread impacts on agriculture and society (Ma et al., 2020). This may trigger the emergence of COVID-19 by disrupting the complex interactions of human-ecology-ecosystems (FAO and UNCCD, 2021). Based on the literature, the impact of drought on these interactions are both direct and indirect affecting the ecosystem services (e.g., inadequate quantity and quality of water, loss of vegetation cover, soil erosion, food shortages), human environment (e.g., inadequate availability of water for drinking and sanitation for hygiene and food) and ecology (e.g., reduction in vegetation, enhances insect immunocompetence, genetic changes in the insects during drought) (FAO and UNCCD, 2021). All these are among the conditions that allow for the spillover of pathogens from natural zoonotic hosts to humans (Mora et al., 2022). Moreover, the modern civilization and the human activities such as farming, deforestation, and infrastructure growth have transformed the native habitats of organisms (Gupta et al., 2021). Also, these activities impact the migration of the reservoirs species and intermediate hosts that carry coronaviruses in specific geographical regions facilitate their transmission to the human host (Gupta et al., 2021).

Consequently, the rapid and global spread of SARS-CoV-2 comes with calamitous ramifications in the nations around the world affecting the public health as well as causing a global financial crisis. Obviously, the disease burden of COVID-19, including asymptomatic infection, hospitalizations and deaths, is increasing dramatically in every country. On the other hand, the economic and social costs of lockdowns and the public measures
to prevent the further spread of COVID-19 also have significant impacts on human well-being.

6. Environmental policy implications of COVID-19

The COVID-19 pandemic highlights the importance of adopting an environmental health approach in order to minimize our vulnerability and improve societal well-being and resilience. This approach could integrate action for better air quality, clean water and better sanitation, and waste management as well as efforts to protect and conserve biodiversity (OECD, 2020). The knowledge, awareness, personal hygiene consciousness management as well as efforts to protect and conserve biodiversity are crucial for human health and well-being and prevent the transmission and contagion from many illnesses.

The syndemic approach could show the ‘modus operandi’ to handle diseases outbreaks. The strategy implications could include preventive measures to protect the biodiversity and the ecosystems, while in regions where human interventions have already shown their destructive behaviours, policy implications could be implemented in order to restore the environmental damage.

Major crises, either economic or environmental, bring opportunities to cogitate the circumstances that contribute or/and trigger them in order to build the society’s resilience. In the case of COVID-19 pandemic, the magnitude of its consequences raises the environmental awareness and consciousness about the interconnection between humans and biodiversity.

The recent sixth assessment report of IPCC (Intergovernmental Panel on Climate Change) press for priority climate actions in the post-COVID-19 world given that human health highly depends on planet health. The pandemic reveals unexpected vulnerabilities in our societies and exacerbates existing weakness. So, in order to be prepared for future crises, actions should be adapted in a ‘systemic’ perspective, including strategy and policy implications for a sustainable development and planning. Among the most important actions that issue from the pandemic are the adaption and mitigation measures to change climate in order to prepare for the projected impacts and adjust to the current effects. Also, the lockdown measures had a great impact on air quality contributing to reduced anthropogenic emissions of air pollutants due to the sudden decrease of the economic and transport activity. These circumstances permitted an ‘ecological study design’ to investigate the air quality while significant emissions of air pollutants were absence. The results show that policy interventions and implications are required to mitigate the air pollution problems including green/environmental technology and the use of renewable and sustainable resources to improve air quality and build resilient cities.

Also, the COVID-19 pandemic has drawn attention to the threat of illegal and unregulated wildlife trade which is a high-risk behaviour, including cultural practices and social or even economic factors, that are associated with the risk of transmission of zoonoses to humans. As we mentioned before regarding the origin of the SARS-CoV-2, the disease outbreak proved the existence of virus reservoirs in wild and domesticated animals, suggesting that illegal trade of living wild mammals was the origin of the COVID-19. So, many scientific researchers recommend a strong and necessary vigilance in long-term coronavirus surveillance studies which are carried out in wildlife and livestock in order prevent potential next outbreaks. Also, they argue for continuous and improved surveillance of wet and seafood markets, biosecurity measurements and early warning programs. Measures should be taken to ensure health and hygiene protocols that limit live-animal and human contact, not only to protect human health but also to preserve the wildlife for a sustainable management of biodiversity.

7. The ecosyndemic framework of COVID-19

Ecosyndemics refer to disease interactions that result from environmental changes commonly caused by humans (Singer, 2009). The term ecosyndemic is an extension of the original syndemic concept, which refers to a set of enmeshed health problems that synergistically interact within the context of noxious biosocial conditions to amplify the overall disease burden on a particular population (Singer, 2013; Singer et al., 2017).

The COVID-19 added to the substantial burden of endemic diseases that has long term effects on structurally vulnerable communities because many of these communities are also disproportionately exposed to meteorological hazards (e.g., extreme weather events), major environmental problems (e.g., deforestation, pollution, urbanization) and social inequalities (Gibb et al., 2020).

Horton (2020) suggests that COVID-19 is a syndemic due to the interaction of non-communicable diseases (NCDs) with the infection of SARS-CoV-2 on a background of social and economic inequalities which exacerbate the adverse effects and the outcome of these diseases. Also, Irons (2020) highlights that COVID-19 exacerbates the disease burden in certain population groups, such as the elderly and people with pre-existing medical conditions that can increase health vulnerability. The response of the syndemic approach to the COVID-19 pandemic needs to include an ecological dimension (Rutter et al., 2020; Kenyon, 2020) that recognizes three major threats to human health and planetary health: communicable diseases, non-communicable diseases, and the environmental issues of climate change and biodiversity loss. These threats are intimately entwined in a global syndemic as they possess common underlying causes.

The syndemic approach to diseases is gaining increasing recognition in the global health research including the research in the current COVID-19 pandemic (Courtin and Vineis, 2021; Rod and Rod, 2021; Calcatera et al., 2022; Robbins Schug and Halcrow, 2022). This approach to health promotion and disease prevention provides an opportunity to approach diseases, including COVID-19, in association with other pre-existing diseases subject to socioeconomic and environmental factors as well as social disparities and health inequalities (Calcatera et al., 2022). These factors influence the transmissibility, susceptibility, infectivity and patient outcomes.

Ramírez and Lee (2021) noted that the emergence of COVID-19 emerged within a broader context of climate and ecosyndemic vulnerabilities. The countries in Latin America have high COVID-19 incidence rates and deaths partly because these countries already experience significant environmental problems as well as chronic underlying preconditions and multiple infectious disease hazards from vectorborne diseases. Apart from infectious diseases, malnutrition, diarrhoea, respiratory illnesses are public health emergencies resulting from the climate change and extreme weather events such as droughts, wildfires, floods and hurricanes (Semenza et al., 2022). Extreme weather patterns, such as heat waves and severe storms disrupt infrastructure access and functionality of public health facilities as well as contribute to weather-related burden of illness and premature deaths (Bell et al., 2018). The smoke from wildfires spreads for thousands of miles. The acute exposure to wildfire smoke causes short-term increases in cardiorespiratory hospitalizations (Shea et al., 2008). Also, particulate matter pollution and ozone pollution events have been linked to asthma attacks, cardiovascular diseases and premature deaths (Shea et al., 2008; Yates et al., 2022). As well as, the increasing temperatures caused by climate change alter the distribution, quantity, and quality of pollen in the air and change the timing and duration of airborne allergens, thus asthma and allergic disease are likely to get worse in a warming world (Shea et al., 2008). Furthermore, important climate-related hazards are the vector-borne diseases because the elevated temperatures and the altered patterns in precipitation regimes lead to longer transmission season which are increased by the expanding seasons and geographic ranges for ticks, mosquitoes and other disease-carrying insects (Semenza et al., 2022).

In addition, the projected adverse effects of climate change on an aging global population make societies more vulnerable to the upcoming public health threats that lead to considerable syndemic interactions. This risk of a severe course of disease after a SARS-CoV-2 infection is highest in countries with high proportion of elderly people (Di Ciaula et al., 2021). The degree of frailty due to aging process and the health deterioration increases the vulnerability and the risk of morbidity and mortality which in turn is
associated with genetic and other external factors (e.g., environmental determinants of health).

Fronteira et al. (2021) support the adoption of a syndemic approach for COVID-19 because SARS-CoV-2 overlaps with endemic diseases and seasonal diseases, a host of cultural and socio-economic determinants, and climate change, air pollution and global environmental change. Moreover, many authors called for effective public health interventions for the prevention of heat-related illnesses and mortality due to the heat waves during the COVID-19 pandemic (Golechha and Panigrahy, 2020; Bose-O’Reilly et al., 2021).

Given that older adults and those with pre-existing health conditions are considered more vulnerable to severe COVID-19 and heat-related illnesses, the heat waves during the ongoing pandemic are of particular challenge to the healthcare systems. Clearly, the challenge of heat waves or other meteorological hazards during the COVID-19 pandemic constitutes an ecosyndemic ‘threat’ to public health because of the interactions between the infection with SARS-CoV-2 and the heat-related illnesses within the population groups.

Many scholars expand the notion of syndemics and include the under-nutrition and/or malnutrition and food insecurity in the framework, besides environmental degradation, infectious disease, chronic disease, and inequity (Persad-Clem et al., 2022; Pryor and Dietz, 2022). Before the advent of COVID-19 pandemic, this referred in the literature as “The Global Syndemic of climate, obesity, and undernutrition” incorporating these three pandemics-obesity, undernutrition, and climate change- in a Global Syndemic that “affects most people in every country and region worldwide” (Swinburn et al., 2019). Currently, the COVID-19 pandemic contributes to unsustainable dietary patterns which have increased the risk of obesity and the risk of COVID-19-related hospitalizations and deaths (Pryor and Dietz, 2022).

According to the above-mentioned study, Swinburn et al. (2019) considered the climate change as a pandemic due to its wide-ranging effects on human health and ecosystems. Both COVID-19 and climate change are transboundary threats that expand in space and time, although their time-scales are different and COVID-19 has a more direct impact on people’s lives (Ebi et al., 2021). The global crisis due to current pandemic does not introduce a completely new threat. Instead, it reveals the routes that human activities contribute to the disruption of ecological balance (James and Steger, 2022). Based on the current research sparked by the massive impacts of COVID-19 in every aspect of human life and the environment, the climate change could lead to the next pandemic (Carlson et al., 2022). Environment-reshaping processes create conditional contexts for the development of syndemic cases. These processes include the natural or man-made disasters and climate change that can induce and/or exacerbate various health problems which may vary across regions (Singer et al., 2022).

In addition, the time period beginning with the Industrial Revolution which was a turning point in humans’ relationship with their environment contributing to ecological destruction has promoted multiple syndemics (Singer et al., 2022). These environmental changes have consequences on human health, wellbeing and safety leading to rapidly growing opportunities for syndemic interaction (Singer et al., 2022).

Furthermore, COVID-19 has become a syndemic through the interaction with air pollution (Aykaç and Etiller, 2022; Yates et al., 2022). A literature review on the impact of various air pollutants on COVID-19 mortality and infectivity conducted by Yates et al. (2022) identified the long-term and short-term exposure to PM2.5, NO2 and O3 as factors that exacerbate COVID-19 incidence and mortality. These studies come from different countries across the globe but they share some similarities. High population density is their common that links the relationship between air pollution and COVID-19 disease burden (Yates et al., 2022). In addition, biological mechanisms have been proposed by which the air pollutants exacerbate the health outcomes in COVID-19 patients (Yates et al., 2022). These are syndemic interactions that are measurable through bio-bio pathways (Singer and Mendenhall, 2022).

This paper has shown that the emergence of SARS-CoV-2 and the global spread of COVID-19 infectious disease is a complex and multi-layered process (Fig. 2). To respond to the pandemic, we propose the ecosyndemic approach which is a relatively new concept in ecological and environmental epidemiology and public health thinking that can enable measures to address the pandemic to be guided by a holistic and comprehensive approach. This approach should include the root causes of syndemics with emphasis on the synergistic interactions on the environmental determinants of health with the social and biological factors that affect individual, population, and

![Fig. 2. Conceptual model of the ecosyndemic framework.](image_url)
public health. The interactions among these different factors amplify the magnitude and the disease burden of the COVID-19 pandemic, which had catastrophic consequences that were far beyond the available capacity to respond effectively.

8. Conclusions and recommendations

Our planet is moving toward to abrupt climate change and ecological crisis. Currently, the COVID-19 has exposed our vulnerability and has revealed the detrimental effects of humanity’s pervasive negative impacts on nature. In the light of the mounting danger of climate change which affects the whole world but disproportionately affects the most vulnerable communities, we suggest a syndemic approach to identify the underlying causes of the COVID-19. Given that the syndemic interactions are facilitated by the worsening patterns of global environmental crisis and climate change, the SARS-CoV-2 may have found suitable conditions that enabled it to emerge and spread globally.

The WHO in March 2021 stated that all hypotheses remained open (https://www.who.int/news/item/30-03-2021-who-calls-for-further-studies-data-on-origin-of-sars-cov-2-virus-reiterates-that-all-hypotheses-remain-open). There is no time to waste on the research topic of the origin of SARS-CoV-2 and the ecosyndemic approach take into account every aspect to solve this question of paramount importance.

Therefore, scientists should be aware of early warning signals that indicate for potential upcoming infectious disease outbreaks. These signals include the environmental, meteorological and climatic conditions which facilitate the emergence of diseases.

In accordance with WHO (2005) the use of climate data for predicting outbreaks of infectious diseases was firstly introduced by Gill (1923) in order to predict malaria based on rainfall and other factors. It is well known that malaria among other climate-sensitive infectious diseases such as cholera, meningococcal meningitis and influenza display seasonal and/or inter-annual patterns (WHO, 2005). Thus, the seasonality of diseases is crucial for the fundamental understanding and control of diseases in order to detect the upcoming outbreak. Generally, influenza outbreaks in the northern hemisphere occur in mid- to late winter, while a peak in malaria transmission follows periods of heavy precipitation (WHO, 2005).

As for the case of COVID-19, it was believed that it could follow a seasonal pattern because respiratory infections caused by HCoVs are generally influenced by meteorological conditions and exhibit seasonal pattern with and/or inter-annual patterns (WHO, 2005). Therefore, the predictable disease seasonal pattern and epidemic peaks could offer early warning signals for the next wave of an outbreak. The probability of disease outbreaks should be based on weather information that are best predictors (e.g. temperature, humidity, rainfall) (WHO, 2021). Moreover, Louw et al. (2022) highlights the role of the high resolution optical imagery of ground data derived from remote sensing applications in the case of COVID-19. For instance, they can be used to identify areas with a high risk of disease transmission or thermal imaging could be used to monitor people in crowded environments and detect possible infected individuals based on body temperature with values higher than normal (Louw et al., 2022). On the other hand, X. Wang et al. (2022) focus on the environmental and wildlife protection in order to prevent pandemic outbreaks. The surveillance of viruses in the environment and in hotspots with a high risk of zoonotic spillover can help identify infectious pathogens. These hotspots are mainly related with human activities that contribute to the destruction of the environment and the deterioration of ecosystems.

In conclusion, the rise in global temperatures, the long-term changes in climate patterns, and the disruption of wildlife habitat could be used as variables in order to predict diseases outbreaks before they arrive, and argue for policies that prevent the arrival of the next pandemic.

CRediT authorship contribution statement

Paraskevi Begou: Writing – original draft, Writing – review & editing. Pavlos Kassomenos: Supervision.

Data availability

No data was used for the research described in the article.

Declaration of competing interest

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

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