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# CO<sub>2</sub> acidification and pandemic situation

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## Objectives

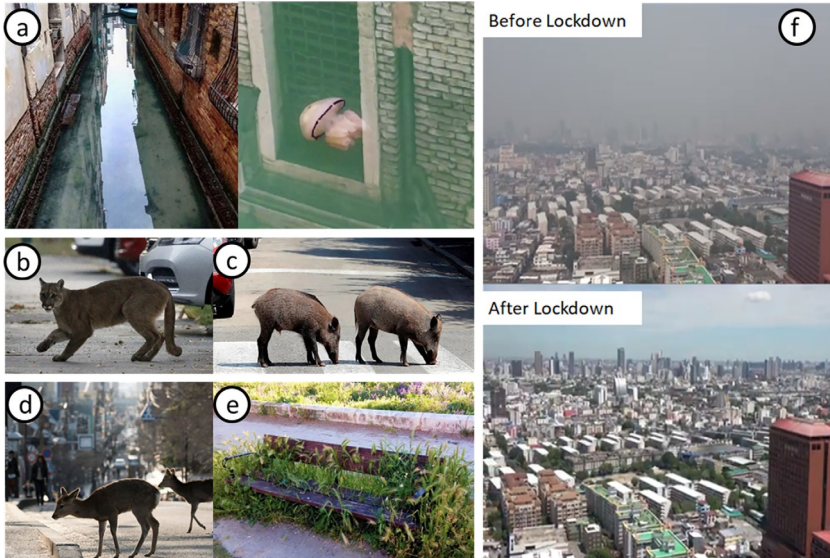
Different objectives and research questions are addressed in this chapter: (a) How the pandemic situation has affected the emissions of CO<sub>2</sub> and its relationship with the acidification in aquatic ecosystems; (b) The influence of the SARS-CoV-2 virus and other viruses on aquatic acidification and risk assessment at ecosystem and human levels; and (c) the role of the virus in lines of evidence and the weight of evidence approach used in the integrative evaluations to quantify pollution, including the CO<sub>2</sub> acidification effects.



## The pandemic situation and the acidification of CO<sub>2</sub> in aquatic ecosystems

There are some authors that have recently pointed out that the situation provoked by the COVID-19 pandemic is a unique opportunity to understand and research ecosystem responses, including the global carbon cycle and the climate system, to the reduction in greenhouse gas (GHG) emissions (Lovenduski et al., 2021; Friedlingstein et al., 2021). Specifically, selected investigations and responses related to CO<sub>2</sub> emission reductions and the relationship with the pandemic situation will be considered here.

Changes produced by anthropogenic activities affect the environment and global cycles, and vice versa. Any attempt to address the difference between the causes and the effects is similar to asking what was first, the chicken or the egg, since it is very likely that the separation between cause and effect is not easily possible (Fig. 1). Although the origin of the virus that caused the SARS-CoV-2 pandemic is still under discussion regarding its zoonotic origin (or not) that jumped from animal to human, it is clearly demonstrated that its human impact is changing our society and its behaviors. Furthermore, the responses of the human population to the virus



**Fig. 1** (A) Clean water from Venice Lagoon with swimming jellyfish ([americadigital.com](http://americadigital.com) image), (B) a puma in Santiago de Chile ([bbc.com](http://bbc.com) image), (C) boars on central streets from North Israel ([elcomercio.pe](http://elcomercio.pe) image), (D) deer in Japan ([bbc.com](http://bbc.com) image), (E) vegetation recolonized urban spaces (EFE verde image), (F) air quality improved in urban areas, such as Bangkok (Thailand) ([Newsflare/ap](http://Newsflare/ap) image).

infection have immediately affected the environment, including the aquatic ecosystem. Returning to the chicken and egg situation, the impact of the virus in the human population also works in the opposite direction, and it is also clear that the environment has significant effects on the infection rate of SARS-CoV-2. We could consider ourselves (humanity) as being in the middle of this dynamic interaction between environment and pandemic situation.

But how do these connections work? Most of the population thinks that the pandemic situation has produced a general improvement in the environment because of lockdowns, the decrease of industrial and commercial activities, cancelation of flights, etc. Some indirect effects of COVID-19 on the environment ([Zambrano-Monserrate et al., 2020](#)) have been especially visible: wildlife “reconquering” cities, air pollution being reduced ([ESA, 2020](#)), noise reduction, significant decrease of waste on beaches and in the landscape due to reduction of tourism, among others—one of the most surprising effects was the water transparency in the Venice Lagoon ([Braga et al., 2020](#)). However, the pandemic situation has also produced adverse

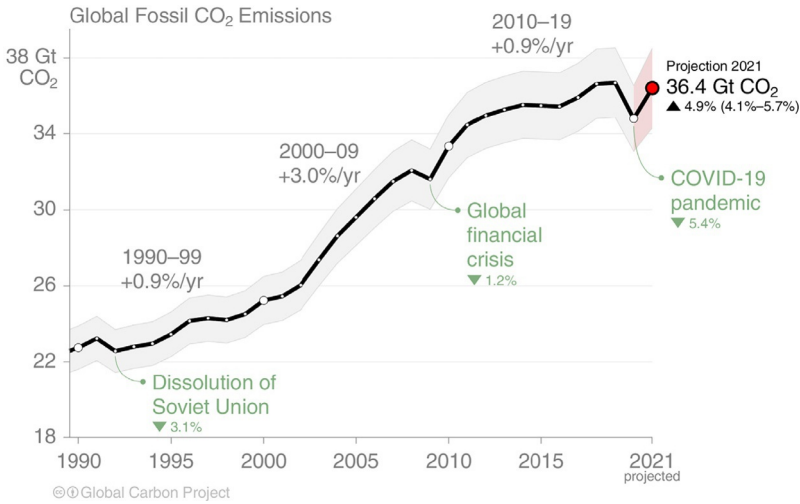
effects on the environment that have not been considered (or it has not been desirable to do so) such as: viral contamination in wastewater and rivers (Rimoldi et al., 2020), the increase of medical wastes and plastic packaging, increase of deliveries and consequent waste generation, house reparation (redecorating), changes in electricity demand, etc.

We must not forget the research conducted in the last few years that identified significant conclusions related to the increase of pharmaceutical compounds concentrations in our environment, especially in the aquatic ecosystems, including the Ocean. In addition, the increase in the production of masks (Calma, 2020) and their waste is a potential problem for the management of this kind of residue, for instance, the impact of plastics, including micro- and nanoplastics, in our aquatic ecosystems should not be forgotten. Furthermore, some water recycling programs were stopped in some cities to avoid virus spread (Zambrano-Monserrate et al., 2020), and the increase in consumption of water, soaps, etc., should be taken into account. All these changes, the harmful and the beneficial, will have a significant impact in the coming years and human generations. In summary, changes in the quality of aquatic, terrestrial, and air ecosystems, and the environment in general will have a direct impact on human health, not only nowadays but also in the future, and vice versa.

It has been generally observed and accepted that one of the most significant effects of the pandemic situation has been a decrease in global carbon dioxide emissions (Le Quéré et al., 2020). It can be observed from Fig. 2 that a sharp decline is associated with the pandemic situation, against the general trend of increasing CO<sub>2</sub> concentration in the atmosphere.

These decreases in CO<sub>2</sub> emissions have been basically associated with the industrial and commercial decrease in the main industrialized countries (Table 1), mainly represented by China, the United States, India, and the European Union, as well as the global oil sector (Friedlingstein, 2021; Global Carbon Project, 2021).

Due to the lockdowns and other strict measures taken in most countries around the world, the production of CO<sub>2</sub> decreased by about 9% during the first half of the year 2020 (Friedlingstein et al., 2021). Although the anthropogenic greenhouse effect is the most pertinent in the global change trends, aquatic ecosystem and especially ocean acidification is also a relevant, yet overlooked, secondary concern. In any case, acidification of aquatic ecosystems is directly associated with the increase in atmospheric CO<sub>2</sub> concentrations. Aquatic ecosystems, in particular the oceans, are a crucial element in offsetting the anthropogenic greenhouse effect. Usually, the



**Fig. 2** Graphic representation of the global fossil CO<sub>2</sub> emissions from the last decades. The 2021 projection is based on preliminary data and modeling. (From Friedlingstein, P., et al., 2021. *Global Carbon Budget 2021*. *Open Access Earth System Science Data Discussions*. <https://doi.org/10.5194/essd-2021-386>.)

**Table 1** Carbon dioxide emissions and growth for the main industrialized countries during 2020 and the projected emissions for year 2021.

Region/ country	2020 emissions (billion tonnes/ year)	2020 growth (%)	2021 projected emissions growth (%)	2021 projected emissions (billion tonnes/year)
China	10.7	1.4	4.0	11.1
United States	4.7	-10.6	7.6	5.1
EU27	2.6	-10.9	7.6	2.8
India	2.4	-7.3	12.6	2.7
All others (incl. IAS <sup>a</sup> )	14.4	-7.0	2.9	14.8
World (incl. IAS <sup>a</sup> )	34.8	-5.4	4.9	36.4

<sup>a</sup>Emissions from use of international aviation and maritime shipping bunker fuels are not usually included in national totals.

Data from Friedlingstein, P., et al., 2021. *Global Carbon Budget 2021*. *Open Access Earth System Science Data Discussions*. <https://doi.org/10.5194/essd-2021-386>.

oceans and other parts of the aquatic ecosystems are natural carbon sinks, or reservoirs, which uptake CO<sub>2</sub> from the atmosphere as part of the carbonic acid equilibrium in solutions. These processes sequester the carbon to the deep ocean where it can be stored for long periods of time without

contact and exchange with the atmosphere of the planet (Barker and Ridgewell, 2012).

It is clear that the impact on the atmosphere and the air ecosystems also directly affects the other ecosystems of the globe, like the aquatic environment. The effects of these significant changes in the aquatic ecosystems remain unknown. These effects are not only (or at least) related to acidification. For instance, they are also related to nitrogen compounds changes in the aquatic ecosystems and their changes in the atmosphere (Kerimray et al., 2020; Zheng et al., 2020). In general, the increase of nitrogen and other harmful chemicals in aquatic ecosystems can provoke eutrophication processes, consuming enormous amounts of oxygen. This produces a significant depletion in the concentration of oxygen in water. The oxygen is needed to sustain life, thus affecting the various aquatic environments.

For all these reasons, and others, the aquatic ecosystems are really complex and dynamic. Thus, aquatic quality improvements can take time to show up and will be site-specific. In general, water needs to infiltrate the ground and will then be filtered (to some degree), partially eliminating some of the contaminants in it. However, some of them will have the ability to reach the groundwater system, in which they can be present for months or years. Furthermore, the transfer to the rest of the hydrological cycle matrices such as lakes and rivers will take additional time. In this sense, most scientists, technologists, and engineers think that improvements to water quality, due to its complex cycle and the level of urbanization occurring, will not be maintained over time unless continuous efforts are made to improve it; only such measures, conducted at site-specific and local levels, will ensure water quality.

We have some data related the pandemic situation and water quality that is locally dependent. India imposed a severe and strict period of lockdown of about 1 month. Most of the industries and commercial offices were closed, reducing the production of waste and contaminants. Some data were reported (Mardon and Mardon, 2020) about water quality in this country and in one of its rivers (Yamuna) that receives freely discharged quantities of contaminants and effluents. The estimation prepandemic was that it received about 40 Hm<sup>3</sup> of waste and sewage every day, with no more than 37% of this receiving any treatment. After the lockdown during March and April 2020, several signs of improvements in the water quality were observed: toxic load was reduced temporarily in the river, water contamination decreased, and suspended particulate matter significantly decreased. In the Ganga River, the fecal coliform reduced from 2200 to 1400 FCC,

and dissolved oxygen increased from 8.3 to 10 mg/L (UPPCB, TOI). However, these positive effects for water quality will not be maintained as, after the end of lockdown, the discharge of contaminants and waste has restarted. Now, the question is: what will be the new water quality situation after the lockdown and the full running of industrial and commercial activities? Due to the environmental improvement results observed during lockdown, this could be the best time to take substantial action and maintain this excellent data for the environment after COVID-19.

However, not all the impacts during the lockdowns and the pandemic are positive for environmental recovery. There are several concerns over the health of water bodies on a longer time scale. For example, one observed consequence was an excessive use of chlorine in water that could generate harmful by-products (Zambrano-Monserrate et al., 2020). During the pandemic, as still today, there has been a tremendous and significant use of single-use plastics and how they are environmentally managed is an issue. Still not enough data is recorded, but the scientific community has been advising for several decades about the problems related to plastics in water bodies, including the ocean. The problem of micro- and nanoplastics in the oceans has been repeatedly raised by the scientific community and included in the research and environmental political actions at European level, among other countries (ECHA, 2018). Microplastics and, particularly, nanoplastics are composed of really tiny particles that are not eliminated in waste water treatment plants and can easily enter living organisms, including humans. The increase of single-use masks mainly composed of plastic (which no doubt have been important in the fight against the pandemic) has raised concerns about how they are environmentally managed, especially regarding the plastic compounds contained within them. The medical waste generated during the pandemic has also increased, and it has been observed piling up and floating in some of our water bodies and coastal waters (Fig. 3).

Countries and authorities must be careful and conduct correct management of these kind of wastes, especially during the pandemic, but also after it. Otherwise, this could be the next significant issue that they will need to deal with if they want to maintain protection of the environment. This will not only be an environmental goal, but a human health and safety need in the future.

The strict relationship between the atmosphere and aquatic ecosystems should be considered carefully when addressing the impact of COVID-19 on their environmental quality and the influence on CO<sub>2</sub> acidification,





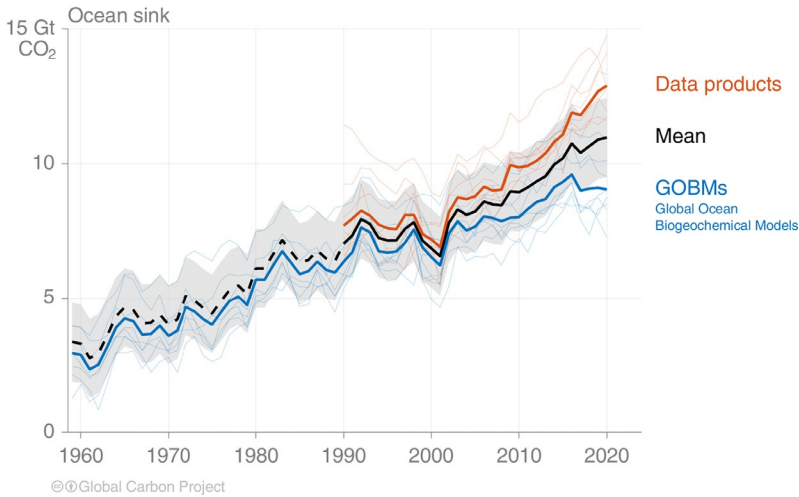
**Fig. 3** Pictures and details of masks and medical care waste that have ended up in the aquatic ecosystem, including the ocean, and how contaminants affect biota.

especially of water ecosystems. We must wait, then, to see the real impact of the pandemic on aquatic ecosystems due to the delay in their responses compared to the atmosphere. Furthermore, we must look at the local level at site-specific studies to understand the impact of the water bodies, and not forgetting the potential long-term effects.

Although different studies have clearly addressed the decrease in the concentration of CO<sub>2</sub> in the atmosphere, at least temporarily, there are no clear studies or results showing the same trend in the ocean. Certainly, there has been no detectable slowing of CO<sub>2</sub> acidification in the ocean or any decrease in the pH values (Fig. 4). The ocean carbon sink, estimated by global ocean biogeochemical models and observation-based data products, continues to increase  $10.2 \pm 1.5 \text{ GtCO}_2/\text{year}$  for 2011–20 and  $11.0 \pm 1.5 \text{ GtCO}_2/\text{year}$  in 2020 (Lovenduski et al., 2021).

After the lockdowns and the beginning of the “new normality” (which is still in progress in most countries), improved by vaccine availability and other global actions, the emissions of CO<sub>2</sub> emissions have reached concentrations similar to the prepandemic situation. It has been pointed out that, even during the pandemic, there were no significant reductions detected in ocean acidification (Lovenduski et al., 2020). In any case, it has been identified and obtained some data and results that informs about a potential positive influence in the water quality as discussed. For instance, Edward et al.





**Fig. 4** Graphic showing the trend of the CO<sub>2</sub> ocean sink during recent decades. The data in the graphic are modeled having been obtained and measured in the field (From Global Carbon Project, 2021. *Global Carbon Atlas*. <https://www.globalcarbonproject.org>.)

(2021) reported positive results in the water quality in the Gulf of Mannar, a shallow bay within the Indian Ocean. After comparison of turbidity data obtained before and after the pandemic, a clear and significant improvement was detected by means of reduction of turbidity in the Gulf waters, mainly related to the decrease in industrial wastes. At the same time, these authors identified an increase in the fish density, which was correlated with the absence of intensive fishing, including potential destructive methods in coral reef areas.

These results identified positive environmental quality effects in the water bodies beyond CO<sub>2</sub> acidification, which is still a key driver in aquatic ecosystem health, but has been demonstrated as not being the only factor affecting aquatic ecosystem quality. As other authors have pointed out (Rizvi et al., 2021), factors such as terrestrial run-off, ocean upwelling, brownification, and water temperature must be examined in the context of COVID-19 consequences to draw strong conclusions about ocean acidification during the pandemic. They have supported this affirmation and proposal using photosynthetic data, as reported by Le Quéré et al. (2020). These authors reported a decrease of chlorophyll-*a* concentration found in phytoplankton in different water bodies of Alaska, northern Europe, southern China, and parts of the United States that was correlated with the decrease in global CO<sub>2</sub> emissions. For instance, a 123 tonnes decrease in CO<sub>2</sub> emissions in China during the pandemic likely resulted in mean

chlorophyll-*a* levels dropping by 5%. This has been explained by the fact that primary productivity decreases when CO<sub>2</sub> emissions decrease. Usually, phytoplankton biomass increases as partial pressure of carbon dioxide ( $p\text{CO}_2$ ) increases because high  $p\text{CO}_2$  adversely affects many primary consumers of algae, like echinoderms, as pointed by different authors in this book (see other chapters in this book, e.g., Riba et al., Riba and Conradi, and by other authors, e.g., Chan et al., 2015). Other effects of this temporary CO<sub>2</sub> decrease (and decrease of  $p\text{CO}_2$ ) could be related to the decrease of echinoderm larva recruitment that will consequently result in greater kelp densities due to less predation by adult echinoderms. The increase of kelp biomass will also have positive effects in fish density, increasing habitats for fish species. On the other hand, this increase in kelp density could have negative effects on the coral seaweed. Thus, this interaction must be addressed in the near future after the situation related to the pandemic is resolved.

It should be highlighted that although most of the above comments on the effects related to the pandemic situation did not show significant negative effects in the aquatic ecosystem, there are no systems in place to monitor global CO<sub>2</sub> emissions continuously and, in general, data reported annually is all that's available. This leaves a big area of uncertainty related to the effects of COVID-19 on aquatic organisms and the acidification of water bodies. Only after the end of the pandemic and additional efforts to address the potential effects will we be able to determine the real impact on the water bodies and in the CO<sub>2</sub> acidification of them.



### **The influence of SARS-CoV-2 and other viruses in risk assessment at ecosystem and human levels**

Changes in the environmental conditions can directly increase the suitability for the transmission of many pathogens, not only airborne but water-, food-, and vector-borne. In recent years, the advance of medicine and socioeconomic development with more intensive public health interventions has significantly reduced the prevalence of infectious disease transmission. However, the advance and increase of different effects associated with climate change, including CO<sub>2</sub> emissions, could negatively affect these eradication efforts. For instance, there has been an increase of about 40% in the environmental conditions suitable for the transmission of a well-known parasite that provokes malaria (*Plasmodium falciparum*). Viruses such as dengue virus, Zika virus, and chikungunya virus have increased their transmission by *Anopheles aegypti* by more than 10% and by 7% for transmission by

*Anopheles albopictus* compared with the data reported in the 1950s. Similar increasing trends are reported by different authors related to the environmental suitability for *Vibrio cholerae*, a dangerous pathogen that is associated with about 100,000 deaths annually (Romanello et al., 2021). In the last 20 years, the coastal area suitable for the transmission of *V. cholera* has increased significantly, reaching more than 90% in some countries located in Africa and South America.

Climate change is a major driver of the increase in the number of dengue virus infections, together with other factors like global mobility and urbanization, which have increased its transmission since the last decade of the 20th century. Furthermore, for the parasite provoking malaria, the influence of the changing climate on the length of the transmission season has increased. Bacteria are also susceptible to increasing transmission related to climate change and new conditions. *Vibrio* bacterium has increased in coastal waters, and is related to human infections such as gastroenteritis, life-threatening cholera, severe wound infections, and sepsis. These increases have been related to different factors, including the increase in the sea surface temperature and salinity values. The data reported by Romanello et al. (2021) estimates an increase in coastal areas of the transmission of these pathogens of about 60% on average around the world.

The connected nature of extreme climate conditions, infectious disease transmission, and decrease in the quality of water ecosystems, including the ocean, represents a concurrent risk that significantly affects human health, especially in the most vulnerable populations, resulting in a reverse trend in public health and sustainable development. What is worse is that, even taking into account all these connections and risks related to climate change, some countries are not working toward adaptation to the new conditions. For instance, the planet has recorded a significant temperature rise in recent decades, together with the increase in the CO<sub>2</sub> emissions and the acidification of oceans and water bodies, and countries must accelerate the adaptation to mitigate and, if possible, avoid the impact of this new situation in populations protecting the health of people all around the Earth.

Until the first months of 2022, most countries have provided at least two (and some of them three or even four) doses of vaccines against COVID-19. However, there is a significant inequity in the availability of vaccine around the world. This fact is the same as that related to the global climate change mitigation response. For instance, at the current rate of reduction, it would take more than 150 years to fully decarbonize the energy system in the

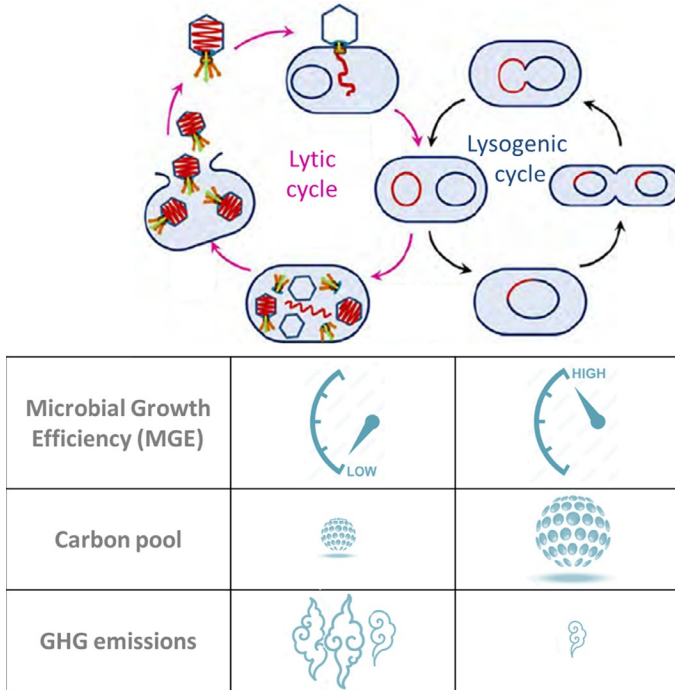
world. The differences found in the response conducted between countries are resulting in a failure of the health benefits of a low-carbon transition at the global level. Neither climate change nor virus transmission and infections know about national borders and laws. In this sense, both actions against climate change and the pandemic situation must be coordinated at a global level with a common global response. For instance, if mitigation efforts to avoid CO<sub>2</sub> emissions do not include the entire planet, they will produce the same response that frontiers have in an accessible vaccination program across all countries and societies. Without a complete availability of vaccines to all the world's population, SARS-CoV-2 and its new variants will represent a risk to human health. There is a real opportunity as a result of this pandemic to achieve improved health, reduced inequity, and economic and environmental sustainability if the world acts together. In summary, the relationships between climate change and COVID-19 provide clear evidence of the need to work together in the world to avoid the health consequences of inequities.

Unfortunately, we may expect humanity's response against climate change will be similar to that combatting the SARS-CoV-2 pandemic: late, unequal, inefficient, and sometimes, in denial.

The large reductions in industrial, transport, and commercial activities during the pandemic resulted in a significant decrease in GHG emissions during 2020. However, this was not a trend maintained beyond that time, and emissions rose again during 2021, demonstrating that the world needs an adequate and coordinated response or the health effects of climate change will worsen throughout the coming decades (Romanello et al., 2021).

There is another consideration in the relationship between pathogens, infections, and climate change. For instance, virus-bacteria interactions could affect GHG emissions and the environmental quality of the aquatic ecosystems.

Although viruses are not nonliving entities without a clear cellular structure, they are the most abundant agents in the world. They have been reported as being capable of influencing global change by means of affecting budgets and GHG cycles and emissions. Bonetti et al. (2019) reviewed and reached conclusions about their capacity to influence global biogeochemical cycles. Their influence is mainly due to infections using bacterial and micro-organism cells and populations that regulate carbon and nutrient turnover. The authors also showed evidence that most of the viruses in aquatic ecosystems, mainly in wetlands, are bacteriophages, being capable of controlling the prokaryotic community. This could have a significant impact on



**Fig. 5** Summarized viral replication mechanisms that might influence the microbial growth efficiency (MGE) and the emissions of GHGs in aquatic ecosystems. (Modified from Bonetti, G., Trevathan-Tackett, S.M., Carnell, P.E., Macreadie, P.I., 2019. Implication of viral infections for greenhouse gas dynamics in freshwater wetlands: challenges and perspectives. *Front. Microbiol.* 10, 1962. <https://doi.org/10.3389/fmicb.2019.01962>.)

ecosystem function, including carbon cycling and GHG fluxes. These authors hypothesized that the rate of greenhouse gas emissions and the pool of sequestered carbon could be strongly linked to the type and rate of viral infection. Furthermore, they propose to increase the studies related to the viral replication mechanism choice that will, consequently, influence the microbial efficiency of organic matter assimilation and thus, the ultimate fate of carbon as a greenhouse gas or stored in soils (Fig. 5).

**The viral replication mechanism can influence microbial efficiency, the carbon sequestration rate, and greenhouse gas emissions in freshwater wetlands**

Viral infection through the reproductive cycle (lytic cycle) is a key process in the biogeochemical cycle of the organic matter that is assimilated

by prokaryotes. During the cycle, this organic matter is returned to the environmental cycle in the form of nutrients and other compounds, once the lysis of the cell is completed after the virus infection. In addition, the viruses positively influence the biodiversity of bacteria in aquatic ecosystems, preventing the dominance of a few species and avoiding niche competition (Mostajir et al., 2015). Viruses can specifically encode polymer hydrolysis that might actively contribute to the degradation of complex polymers into smaller forms. These smaller compounds could then be accessible to microbes, thus boosting CO<sub>2</sub> and CH<sub>4</sub> production (Emerson et al., 2018; Trubl et al., 2018).

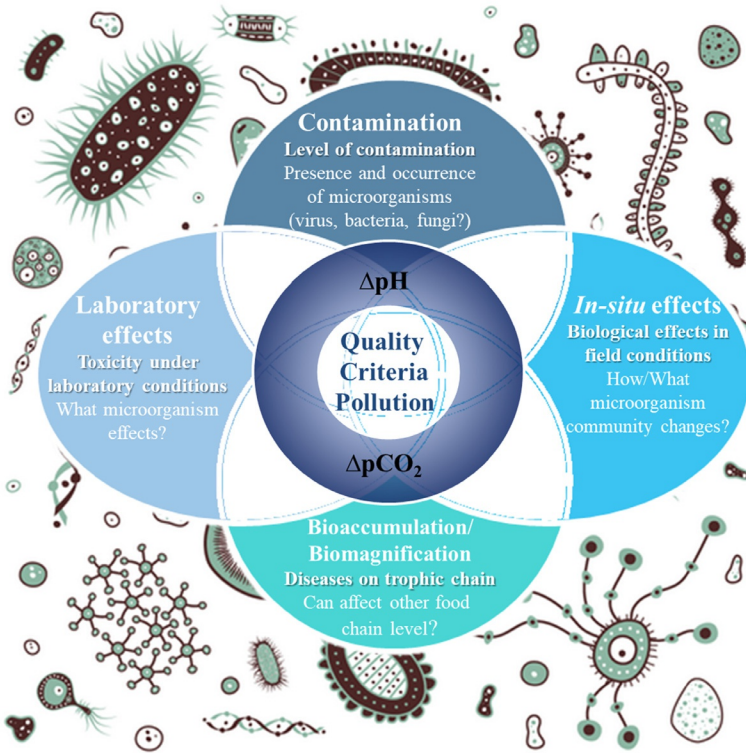
A strong infection will increase the rates of recycling of the sedimentary organic matter through the virus and pathogen channel, which will result in an increase in CO<sub>2</sub> or CH<sub>4</sub> production. It will also have significant negative consequences on carbon cycling and nutrient regeneration in aquatic ecosystems, especially in wetlands, as has already been demonstrated in marine ecosystems (Corinaldesi et al., 2012). Therefore, greenhouse gas emissions are strongly linked to infection rates (Fig. 5), and thus, viruses should be considered in global plans and strategies for the management of wetland ecosystems.



### **The role of viruses and microorganisms in the weight of evidence approach to quantifying pollution**

The integrated method based on a weight of evidence (WoE) approach links the set of data from different lines of evidence, as previously reported in some chapters of this book (Riba et al.). The role of viruses and pathogens in the application of the WOE is defined depending on its inclusion in any of the lines of evidence integrated in the WOE. Each one of the LoEs should be discussed under a comparative point of view.

The first question addresses about the use of microorganisms, including viruses, as part of the lines of evidence is to understand if their responses can be considered as part of the ecosystem response (LoE “in situ alteration”), or part of organisms responding to exposure to contaminants (LoE “toxicity”) as measurements to address the adverse effects related to anthropogenic activities. Furthermore, these organisms could be considered as part of the LoE of contamination, understanding them as a cause of the adverse effects (LoE “contamination”). It should be defined in the conceptual model as shown in Fig. 6.



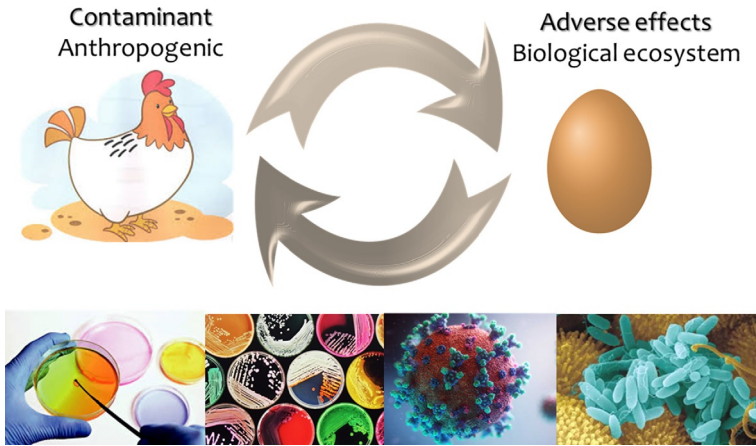
**Fig. 6** Synoptic representation of the integrated methods designed under weight of evidence to address the pollution in aquatic ecosystems affected by  $\text{CO}_2$  acidification. It includes microorganisms as part of the LoEs.

Defining the role of the virus and other microorganisms, we reach again a chicken/egg situation when we want to address the following questions (Fig. 7):

- (a) Is (or is not) the presence and activities of the pathogens a consequence of the adverse impact of anthropogenic activity?
- (b) Are they part of the organisms that can feed the integrated method WoE to address the adverse effects, either as community and population under in situ assessment (bacterial population) or as organisms responding to contamination using toxicological assessment under laboratory conditions (e.g., Microtox)?

The first issue requires understanding of the role of these pathogens in the WoE, and should clearly answer the question regarding their origin: are these pathogens used in WoE as a consequence of anthropogenic activities?





**Fig. 7** Graphic representation of the chicken/egg situation related to the inclusion of viruses and other microorganisms as part of WoE.

We must return to initial chapters of this book (DelValls and Riba, Riba et al.) to recall the definition of contamination and pollution that has been used during the whole book to define the use of LoE, WoE, and in general, the risk assessment proposed here.

## Scenario 1

Viruses and other pathogens are a consequence of anthropogenic activities. In this case, they are considered contaminants and then included in the LoE to characterize contamination and considered a cause of potential pollution. In addition, they can be used in other LoEs as toxicity, in situ alteration assessment (ecological integrity), and even in specific cases, as part of LoE bioaccumulation (Fig. 6).

Some examples of Scenario 1 could be the increase of organic matter or urban wastes in water bodies. It can produce the proliferation of some specific pathogens, for instance *Escherichia coli* (*E. coli*). In this case, a microorganism (usually healthy inside humans and other organisms) become a contaminant. If its proliferation is associated with biological adverse effects (e.g., human diarrhea), we can conclude that it becomes a pollutant.

As part of this scenario, and to characterize the potential biological adverse effects produced by *E. coli*, other microorganisms can be used at laboratory level and/or in situ conditions. In addition, a monitoring of their

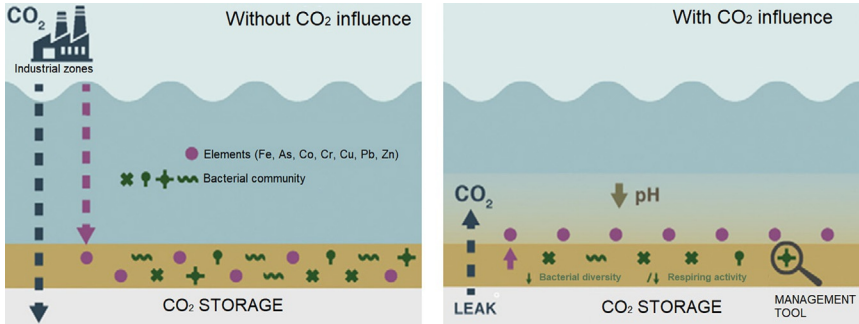
transfer through the trophic chain could be informing about a potential processes of bioaccumulation and/or biomagnification.

## Scenario 2

Viruses and other pathogens are not a consequence of anthropogenic activities. In this case, they are not considered contaminants and, therefore, their adverse effects cannot produce pollution. For instance, a natural appearance of a virus or pathogen that produces adverse effects cannot be considered under WoE as it has been defined in this book. It is the same as the case where a natural volcano eruption produces lot of contaminants and some of them have adverse effects; in which instance, the increase of compounds such as SO<sub>2</sub>, SO<sub>3</sub>, or other gases in air and/or water is not contamination and their adverse effects not pollution, unless it is demonstrated that the eruption of the volcano was provoked by anthropogenic activities.

There are results related to the use of bacterial communities to address the impact of CO<sub>2</sub> acidification in aquatic ecosystems (Borrero-Santiago et al., 2017). Borrero-Santiago et al. (2017) demonstrated that bacterial responses at community level (total number of cells, respiration, composition, and diversity) under different CO<sub>2</sub> acidification scenarios in contaminated sediments were valid and robust to be part of a WoE approach to address the pollution associated with the acidification (Fig. 7). They reported that a CO<sub>2</sub>-enrichment may remove elements from the ecosystem affecting bacteria. They also identified that bacterial communities can adapt to different acidification scenarios by means of modifying the diversity and their structure. Regarding respiration, acidification scenarios provoked a negative impact, suggesting this indicator as useful to be included in the WoE for environmental risk assessments in aquatic ecosystems (Fig. 8).

As previously discussed in different chapters of this book, the WoE approach must answer the four questions related to the environment and human health (Fig. 6). Furthermore, the method must distinguish the biological effects related to CO<sub>2</sub> and acidification (increase of concentration of protons, CO<sub>2</sub>, etc.) from those associated with the physicochemical changes in the equilibria of substances and contaminants in the aquatic ecosystem impacted and/or affected by the acidification. In the case of considering viruses and microorganisms as contaminants, it should be addressed in the same way described previously in this book when CO<sub>2</sub> acidification is considered. In this chapter, the interactions between viruses and bacteria and their influence on GHG emissions has already been discussed. These



**Fig. 8** Schematic description of the main differences observed in bacterial communities exposed to different CO<sub>2</sub> acidification scenarios (Borrero-Santiago et al., 2017).

questions should be included as part of the WoE to characterize the potential risk assessment in aquatic ecosystems.

In addition, the methods to link the different LoEs should be valid when using viruses and microorganisms, following the postulates included in any of the different approaches discussed in this book. Only the specific responses of viruses and pathogens must be identified to be included in the integration methods and, as stated, the main task is to identify an anthropogenic origin or not in the proliferation of viruses and microorganisms before applying the WoE.

In Scenario 1, if viruses and pathogens are considered contaminants, the WoE should have as a final objective in the risk assessment the establishment of environmental quality values for them (if related to pollution), similarly to the calculation of other contaminants' quality values. Thus, these values for viruses/microorganisms and other contaminants (acidification, metals, etc.) will allow classification of the ecosystems according to the degree of environmental deterioration. In this way, its application allows taking the necessary measures for the recovery of the ecosystem quality or, if this is not possible, preventing the possible alteration of others. It is also possible to obtain these types of values related not only to environmental matrices to classify the environmental quality of their ecosystems, but also and in a similar way, for biological tissues. In this case, the objective is to determine the quality of the biological material and the organisms according to their degree of biological deterioration, based on the concentrations of contaminants and the effects that they produce on the organisms and/or their tissues.

At the risk of being repetitive in this chapter and others in this book, it should be clearly stated that the concept of environmental quality values is

closely related to the **difference between the terms contamination and pollution**. The introduction by man of matter or energy (viruses and microorganisms included) into the aquatic environment can lead to different responses from the receiving ecosystems. On the one hand, they can produce adverse effects that damage living resources, endanger human health, and hamper aquatic activities, including fishing. This type of response would correspond to the term pollution. On the other hand, these anthropogenic contributions may not produce adverse effects on aquatic living resources. In this case, the use of the term contamination is proposed. Similarly, these definitions could be used to obtain the biological tissue criteria. Thus, the concentrations of pollutants that bioaccumulate in the tissues of organisms but do not produce sublethal effects on them will be less harmful (although they could be subjected to a biomagnification process) than those that are associated with sublethal effects, such as those determined by biomarkers of effect (not exposure), as in the case of histopathology. The difference between these two types of concentrations will be the one that allows calculating and establishing the quality values of biological tissue. The application of these quality values to real cases allows the initial classification of the environmental (or human health) risk associated with an episode of contamination in a given situation and can be related to acidification, viruses/pathogens, and/or other sources of contamination.

In order to obtain a real measure of the state of an ecosystem using WoE, all available information is integrated (concentration of contaminants, including viruses and pathogens—cause; and biological adverse effects under laboratory and field conditions, including responses of microorganism—effect) through the different techniques used, in order to obtain a global index and quality values of the environmental quality status of each of the areas included in the study (Conradi and Riba, 2022; Riba et al., 2022).

There are some main conclusions in the revision described in this chapter in relation to the environmental risk assessment in CO<sub>2</sub> acidification water ecosystems and its relationship with the pandemic situation:

- (1) During the pandemic there were strict lockdowns in most of the world, especially in industrialized countries. This provoked a significant decrease of CO<sub>2</sub> emission to the atmosphere, albeit not maintained over a long period of time, with emissions increasing again during the year 2021 and first months of 2022.
- (2) The decrease of the CO<sub>2</sub> emissions and the decrease in traffic, industrial, and commercial activities produced little or no positive effects on the

CO<sub>2</sub> acidification in water bodies, including the ocean. Future monitoring programs should address the potential positive effects at large and global scales. However, few positive effects were measured at local levels in water bodies and coastal areas in other indicators, such as decrease of turbidity, decrease of contaminants and garbage, increase of fisheries, etc.

- (3) The pandemic situation has identified the lack of coordination in conducting efforts to solve problems, such as difference in the vaccine availability, that were compared positively with the mitigation efforts to avoid climate change, including GHG emissions.
- (4) There are potential adverse effects associated with the pandemic situation that will be (or not) identified in the future and that are related to the increase of plastic wastes (masks) and medical care utilities, reagents, and medicines.
- (5) The virus can affect GHG emissions and the geochemical cycle of carbon in water bodies by affecting the microorganisms related to the organic matter degradation.
- (6) Virus and other microorganisms can be used as part of WoE to address risk assessment in aquatic ecosystems associated (or not) with acidification. The main task is to address if they should be considered a cause of pollution or just part of the ecosystem.
- (7) The use of an integrated approach based on a weight of evidence can be a powerful and useful tool to be used in an environment risk assessment and characterization, able to distinguish the differences in the pollution among the contamination sources, including viruses and other microorganisms that are causing adverse biological effects in aquatic organisms. In addition, calculating environmental quality guidelines is highlighted in order to monitor the environmental degradation related to the presence of these microorganisms and the enrichment of CO<sub>2</sub> in aquatic ecosystems, and to classify the critical areas where especial attention must be applied.

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