The role of outdoor and indoor air quality in the spread of SARS-CoV-2: Overview and recommendations by the research group on COVID-19 and particulate matter (RESCOP commission)

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Accepted 24 February 2022

A R T I C L E I N F O

Keywords:
COVID-19
Air quality
Air pollution
Indoor environments
Ventilation
CO2 monitoring

A B S T R A C T

There are important questions surrounding the potential contribution of outdoor and indoor air quality in the transmission of SARS-CoV-2 and perpetuation of COVID-19 epidemic waves. Environmental health may be a critical component of COVID-19 prevention. The public health community and health agencies should consider the evolving evidence in their recommendations and statements, and work to issue occupational guidelines. Evidence coming from the current epidemiological and experimental research is expected to add knowledge about virus diffusion, COVID-19 severity in most polluted areas, inter-personal distance requirements and need for wearing face masks in indoor or outdoor environments. The COVID-19 pandemic has highlighted the need for maintaining particulate matter concentrations at low levels for multiple health-related reasons, which may also include the spread of SARS-CoV-2. Indoor environments represent even a more crucial challenge to cope with, as it is easier for the SARS-COV2 to spread, remain vital and infect other subjects in closed spaces in the presence of already infected asymptomatic or mildly symptomatic people. The potential merits of preventive measures, such as CO_2 monitoring associated with natural or controlled mechanical ventilation and air purification, for schools, indoor public places (restaurants, offices, hotels, museums, theatres/cinemas etc.) and transportations need to be carefully considered. Hospital settings and nursing/retirement homes as well as emergency rooms, infectious diseases divisions and ambulances represent higher risk indoor environments and may require additional monitoring and specific decontamination strategies based on mechanical ventilation or air purification.

1. Introduction

The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is the etiologic agent of the COVID-19 pandemic. The incubation period of COVID-19 lasts from 2 to 12 days, with an average of 5.1 days and several possible symptoms (Lauer et al., 2020). Enormous international scientific efforts across a range of disciplines are underway to understand the factors determining the transmission and infectivity of the new coronavirus, with the aim of minimizing its spread, reducing the diffusion rate and developing new therapeutic treatments or vaccines. Healthy people probably most commonly get infected via inhalation of viral particles spread by patients during normal speaking, sneezing and coughing (Chatterjee, 2020). However, it is necessary to consider the possibility of SARS-CoV-2 spreading via other routes than by infected droplets (Morawska and Cao, 2020). Surfaces touched by infected persons, water and sewage, garbage, or soil may also represent routes of viral spreading, but their relative contribution remains contentious (Onakpoya et al., 2021). As resulting from the review performed by Marquès and Domingo (2021), SARS-CoV-2 can last several hours or even few days on different surfaces, but it can be inactivated by using the common available disinfectants and biocides. Consequently, it seems that the persistence of SARS-CoV-2 on inert surfaces should not be regarded as an issue of special concern for the transmission of the new coronavirus if compared to the main airborne contagion route through aerosols Marquès and Domingo (2021).

The main transmission route of SARS-CoV-2 seems to be the droplet route (particles >5 μm) (Jin et al., 2020). However, on May 2021 the CDC updated their COVID-19 prevention guidelines specifically referring to the SARS-COV2 transmission also from aerosolized particles ("inhalation of very fine respiratory droplets and aerosol particles") that are much smaller than large respiratory droplets and can remain suspended in the environment – especially indoor – for minutes or possibly hours, thus "increasing the amount of viral particles to which a person is exposed". Actually, CDC recognized that "once infectious droplets and particles are exhaled, they move outward from the source" and that the transmission of SARS-COV2 may occur also at distances greater than six feet (2 m) from the infectious source, despite it being less likely than at closer distances (CDC, 2020). There is debate about how long viral particles can remain infectious while suspended in air. Regardless, the risk for infection decreases with increasing distance from the source and increasing time after exhalation. "Heavier respiratory droplets containing the virus fall to the ground or other surfaces under the force of gravity and the very fine droplets and aerosol particles remain in the air stream" (CDC, 2020), being progressively diluted in relation to the growing volume and streams of air they encounter. The progressive loss of viral viability and infectiousness over time is also influenced by environmental factors such as temperature, humidity, and ultraviolet radiation such as sunlight (CDC, 2020). Such factors may be key contributors to the emerging seasonal pattern of SARS-CoV-2 epidemic waves.

1.1. *COVID-19 and air pollution: the research group on COVID-19 and particulate matter (RESCOP)*

The potential relationship between COVID-19 epidemic waves and air pollution poses tantalizing questions. Domingo et al. (2020) suggested that the burden of COVID-19 is more severe in those areas characterized by higher levels of particulate matter (PM). Setti et al. (2020a) observed an association between the number of Italian provinces with daily averaged PM10 concentrations exceeding the European limit values (set at 50 $\mu g/m^3$) and the subsequent number of COVID-19 cases. Significant associations were found between mean concentrations of PM2.5 during the month of February 2020 and the total number of Italian COVID-19 cases on 31 March 2020. These ecological analyses need to be seen with great caution. However, Setti et al. (2020b) also evidenced that air samples collected from open spaces in the industrial zone in Bergamo province were positive for SARS-CoV-2 RNA. Researchers demonstrated viral RNA in 30% of PM10 (particulate matter) of outdoor air samples (Setti et al., 2020b). Research carried out by the Harvard School of Public Health confirmed an association between increases in particulate matter concentrations and mortality rates due to COVID-19 (Wu et al., 2020a).

An international research group was initially fostered by the Italian Society of Environmental Medicine (SIMA) with the aim of investigating possible links between COVID-19 and particulate matter, as well as the topic of indoor air quality in relation to COVID-19 diffusion (RESCOP, *Research Group on COVID-19 and Particulate Matter*). Starting from this initiative, *Environmental Research* (Elsevier journal) established the RESCOP thematic Commission on COVID-19 and outdoor/indoor air quality, which has promoted a Special Issue devoted to this specific topic, resulting in the submission of about 150 papers and publication of 76 of them from all over the world.

The primary objective of the RESCOP Commission was to involve international experts already working on these specific topics by developing analytical protocols according to which it could be possible to confirm or exclude the presence of SARS-CoV-2 RNA in indoor environments or on outdoor particulate matter, as well as performing specific assessments of the potential persistent viability and virulence (infectious potential) of the virus load eventually detected on particulate matter and indoor environments. Obviously, detection of viral genomic material alone does not prove the presence of intact virus and infectivity.

The secondary objective of the Commission was to examine whether the viral detection on PM10/PM2.5 could be used as early indicator of COVID-19 epidemics recurrence, and whether such information could be used for preventive purposes. Searching for SARS-COV-2 could be implemented also to assess contamination of indoor environments such as hospitals, ambulatories, restaurants, shopping malls, shops, factories, pubs, as well as airplanes, trains, cruise ships etc.

The third objective of the Commission activities was to deepen the virus diffusion and health aggression models in relation to pollution parameters. Information coming from the articles published by the Commission on the Special Issue are expected to add knowledge about virus diffusion, COVID-19 severity in most polluted areas, inter-personal distance requirements and need for wearing face masks in indoor or outdoor environments as well as to whether one should change recommendations for inter-personal distance in specific circumstances.

Moreover, the research outcomes might help to highlight the need for maintaining particulate matter concentrations at low levels for multiple health-related reasons, including potentially the spread of SARS-CoV-2 (Setti et al., 2020a). The levels of particulate matter and NO_2 should be as much as possible close to the new thresholds recently set by WHO in the updated Air Quality Guidelines presented in September 2021 (WHO, 2021).

1.2. Environmental determinantsof SARS-CoV-2 transmission

The systematic review carried out by Maleki et al. (2021) reported that the main transmission route of SARS-CoV-2 is the droplet route (particles> 5 μm) (Jin et al., 2020). However, Mecenas et al. (2020) showed that low humidity and temperature may increase the vitality of SARS-CoV- 2 in an aerosol. This aspect is particularly important in relation to indoor environments because – according to Morawska and Cao (2020) and Paules et al. (2020) – small aerosol particles with a higher viral load probably can be transferred up to 10 m from the emission source. On the other side, the persistence of SARS-CoV-2 in hospital wards (COVID-19 outbreak) in Wuhan was confirmed by the number of virus copies (from 1 to 42 copies/m^3) in a study of Liu et al. (2020a).

1.3. COVID-19 increased risk of transmission in indoor environments: possible preventive measures

Specific preventive measures should be seriously considered for indoor environments and public transportations, given the potentially increased risk of SARS-CoV-2 transmission in case of inadequate ventilation or air handling in enclosed spaces, within which “the concentration of exhaled respiratory fluids, especially very fine droplets and aerosol particles, can build-up in the air space” (CDC, 2020). The risk is higher in those crowded indoor environments where prolonged exposures (>15 min) and exhalation of infected respiratory fluids may increase by some activities (e.g. from physical exercise, raised voice such as shouting, singing etc.).

Physical distancing and use of well-fitting masks may not be enough in crowded, high-risk activities. In this perspective, the added value of specific systems for Indoor Air Quality monitoring needs further research. Di Gilio et al. (2021), validated that CO_2 portable monitors (10 cm × 10cm) can be used to assess the potential risk of infected droplets/aerosols inhalation when CO_2 levels reach a defined threshold (fixed at 700 ppm in more recent studies) and foster the natural ventilation of the space by simply opening doors and windows for the time needed to reduce CO_2 levels. Of note, normal breathing of a child aged 7–9 years old generates 14 L of CO_2 per hour, which is 50% lower than the amount produced by a teenager, while in conditions of moderate physical activity, a 15 years old student can release up to 85 L of CO_2 per hour. In addition, air purifiers or controlled mechanical ventilation (CMV) devices (when certified by scientific reports concerning their safety and efficacy in air dilution and particles’ removal) could be installed to allow a correct and constant air exchange of indoor environments without the need of opening the windows or where natural air exchange is not sufficient to remain below the threshold of 700 ppm.

Formal decision and cost-effectiveness analyses are needed to establish the utility of such monitors and devices and how widely they should be adopted, if at all. Obviously, the level of epidemic activity and the fatality rate in an area may affect the cost-effectiveness ratios. These ratios may also change as different viral strains of different infectivity become dominant and as fatality rate decreases sharply with some interventions, primarily vaccinations. Based on current knowledge, the minimum functional standard is represented by decentralized double flow CMV with pre-filtration of the incoming air (that can be heated in the winter months so as not to reduce the indoor gradient of temperature). The air flow per hour to be exchanged must be determined in m^3considering the volume of indoor space. For a room of 90 m^3, 10–15 cycles per hour of complete air exchange are needed to mitigate the risk of breathing in infected material. This corresponds to 900–1400 m^3 of air in entrance and the same extracted from the indoor environment each hour. However, taking into account the high cost of the abovementioned technologies, a cost-effective system could be represented by the installation of continuous air extractors which can allow huge amount of air exchange by simply extracting indoor air from the enclosed spaces (rooms, offices, etc.) thus facilitating the maintenance of good air quality from natural ventilation through windows and door openings.

If choosing centralized systems, it should be highlighted the issue of expensive and continuous sanitizing of air ducts. Furthermore, air purification systems (able to kill bacteria and viruses) may be considered – especially for indoor public settings – making sure that they use high performance HEPA filters or ULPA filters DFS capable of nanometric disinfectant filtration (removal of nanoparticles).

Concerning special indoor environments such as hospital settings and nursing/retirement homes, tested by Zupin et al., (2021), further research should determine whether there are warning thresholds of indirect indicators of contagion risk (i.e. CO_2) and assess the viability and infectivity potential of SARS-C0V-2 present in the air of COVID hospitals, ambulances and emergency rooms.

Once cost-effectiveness issues are addressed by non-conflicted studies and further evidence accumulates, EU Member States’ Governments may foster and develop financial mechanisms to support the adoption of the most appropriate systems to reduce the risk of contagion on public transportations (trains, buses, airplanes, cruise ships etc.) and indoor environments (i.e. schools, banks, offices, workplaces, halls, hotels, theatres, cinemas, disco etc.). Specific pilots are under development by several organizations such as the United Nations International Center for Genetic Engineering and Biotechnology (ICGEB) for the treatment of indoor air inside cruise ships, and by the Italian Society of Environmental Medicine for museums.

A Reference Guide for Indoor Air Quality (IAQ) management and monitoring may be adopted in each indoor public setting - starting from schools and Universities - with a IAQ coordinator appointed to address the most common issues related to IAQ management.

1.4. HVAC and local exhaust ventilation systems

Borro et al. (2021) and Aghalari et al. (2021) have demonstrated that SARS-CoV-2 is mainly transmitted through exhalations from the airways of infected persons, so that Heating, Ventilation and Air Conditioning (HVAC) systems might play a role in spreading the infection in indoor environments. Borro and colleagues modeled the role of HVAC systems in the diffusion of the contagion through a Computational Fluid Dynamics (CFD) simulations of cough at Vatican children’s hospital in Rome. Both waiting rooms and hospital rooms were modeled as indoor scenarios. A specific Infection-Index (η) parameter was used to estimate the amount of contaminated air inhaled by each person present in the simulated indoor scenarios. The potential role of exhaust air ventilation systems placed above the coughing patient's mouth was also assessed.

Their CFD-based simulations showed that HVAC air-flow remarkably enhances infected droplets diffusion in the whole indoor environment within 25 s from the cough event, despite the observed dilution of saliva particles containing the virus. In the waiting room simulation, the Infection-Index (η) parameter increases the faster the higher the HVAC airflow. Greater flows of air conditioning correspond to greater diffusion of the infected droplets.

The proper use of Local Exhaust Ventilation systems (LEV) simulated in the hospital room reduced infected droplets spreading from the patient's mouth in the first 0.5 s following the cough event. In the hospital room, the use of LEV system reduced the η index computed for the patient hospitalized at the bed next to the spreader, with a decreased possibility of contagion.

1.5. *Other interventions with potential effect on COVID-19 spread*

Grimalt et al. (2021) performed a systematic sampling and analysis of airborne SARS-CoV-2 RNA in different hospital areas including ICU rooms to assess viral spread, finding out the highest occurrence of RNA in the rooms with COVID-19 patients and the adjacent corridor. There was a significant transfer of viruses from the COVID-19 patients' rooms to the corridors, while patients intubated and connected to respirators that filtered all exhaled air resulted in significantly lower viral concentrations in adjacent corridors. Systematic air filtration was performed in rooms with COVID-19 infected and uninfected patients, in corridors adjacent to these rooms and intensive care units, and in open spaces, showing the opportunity to use ventilation systems in order to minimize possible contagion risk, as well as the importance of direct monitoring of SARS-CoV-2 in the air of indoor environments to prevent unexpected viral exposures.

Building design strategies may also be important to consider in mitigating threats to occupants. The review by Megahed et al. (2021) aims to draw architects' attention towards the high risk of airborne transmission of diseases by providing the latest updates and solutions to better understand the environmental and health issues associated with COVID-19. Based on the complexity of the problem and the need for interdisciplinary research, this study presents a conceptual model that addresses the integration of engineering controls, design strategies and air disinfection techniques.

Finally, some of the societal and individual-level measures used to curb COVID-19 transmission may have effects on air quality. For examples, lockdown measures had drastic impacts on social and economic situations, but they may have generated some positive (even if short-lived) impacts on the environment. Recent data released by National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) indicate a reduction in the levels of environmental pollution particularly in dimensions of air pollution across the megacities of the globe (Khan et al., 2021). On the other side, Dargahi et al. (2021) have demonstrated the presence of SARS-CoV-2 virus in the internal and external surfaces of various masks used by patients and staff with SARS coronavirus, as well as the possibility of airborne transmission in Imam Khomeini Hospital of Ardabil (Iran).

1.6. *Air pollution and COVID-19*

Previous research has assessed the presence of SARS-CoV-2 in outdoor air particulate matter (PM) in urban areas of Northern Italy and USA (Setti et al., 2020a). Linillos-Pradillo et al. (2021) investigated the presence of SARS-CoV-2 RNA in outdoor air samples (on PM10, PM2.5 and PM1). Six samples of PM10, PM2.5 and PM1 were collected between May 4th and 22nd 2020 in Madrid, on quartz fiber filters by using MCV high volume samplers (30 m^3 h^{-1} flow) with three inlets (Digitel DHA-80) for sampling PM10, PM2.5 and PM1. RNA extraction and amplification was performed according to the protocol recently set by Setti et al. (2020b) in Italy. No presence of SARS-CoV-2 in quartz fiber filters samplers for PM10, PM2.5 and PM1 fractions was observed. The authors concluded that the absence of viral genomes could be due to different factors including: limited social interactions, masks, and economic activities resulting in reduced circulation of the coronavirus, lower daily PM concentration in outdoor air, and higher temperature that characterizes spring season.

Wu et al. (2020b) described the challenges and outline promising directions and opportunities concerning the assessment of long-term exposure to air pollution and possible increase in the severity of COVID-19 health outcomes, including death. The same authors had already highlighted that higher historical PM2.5 exposures in the U.S. were positively associated with higher county-level COVID-19 mortality rates after accounting for many area-level confounders (Wu et al., 2020a).

At this stage, research published is yet inconclusive regarding the role of air pollution on the geographic spread of the disease both regionally and globally. Further studies and more systematic research on the relationship of air pollution and COVID-19 should be encouraged and conducted. Of course, there are many other reasons to act decisively on reducing air pollution, besides any direct effect on COVID-19 transmission. Exposure to ambient air pollution is related to 4.2 million premature deaths per year worldwide (WHO 2021) and it is associated with a variety of adverse health outcomes, such as respiratory and cardiovascular morbidity. Furthermore, exposure to air pollution can increase human sensitivity to respiratory pathogens via damage to the respiratory track or via airborne transmission on the surface of particulate matter, and might represent an additional factor influencing COVID-19 morbidity and mortality rates.

Barnett-Itzhaki et al. (2021) examined the association between population-weighted long term exposure to PM2.5 and NOx, and the morbidity and mortality over time following the detection of the first COVID-19 positive case in 36 OECD countries. They found that PM 2.5 concentrations in 2015–2017 were positively correlated with COVID-19 morbidity and mortality after 10, 20, 40 and 60 days since the first confirmed case in all countries. NOx concentrations in 2015–2017 and country's density (population/km^2) were also positively correlated with COVID-19 morbidity and mortality on the 60th day. All multivariate linear regressions of PM2.5 concentration models showed consistent signals. The authors concluded that long-term exposure to air pollutants concentrations exceeding WHO 2005 guidelines might exacerbate morbidity and mortality rates from COVID-19.

These results should be validated carefully given their ecological design. However, they could raise another red flag globally among decision makers about the need of reducing air pollution and its harmful effects.

The questioned link between air pollution and COVID-19 spreading or related mortality represents a hot topic that has immediately been regarded in the light of divergent views. Becchetti et al. (2021) analyzed available literature concerning the link between air quality, as measured by different pollutants and a number of COVID-19 outcomes, such as the number of positive cases, deaths, and excess mortality rates documenting the existence of substantial evidence produced worldwide concerning the role played by air pollution on health in general and on COVID-19 outcomes in particular. These results support both long-term exposure effects and short-term consequences (including the hypothesis of particulate matter acting as viral "carrier"). The authors concluded that the link between air pollution and COVID-19 outcomes is corroborated by several different research methodologies. It can be argued, therefore, that policy implications should be drawn from a rational assessment of these findings as "not taking any action" represents an action itself. In this perspective, interesting work has been performed by the Scientific Foresight Unit (STOA) of the European Parliament Research Service (EU Parliament, 2021).

De Angelis et al. (2021) carried out an ecological study to assess the association between long-term exposure to particulate matter (PM) and NO_2 on COVID-19 incidence and all-cause mortality taking into account demographic, socioeconomic and meteorological variables. Several demographic and socioeconomic variables were associated with COVID-19 incidence and all-cause mortality. An increase in average winter temperature was associated with a non-linear decrease in COVID-19 incidence and all-cause mortality, while an opposite trend emerged for the absolute humidity parameters. An increase of 10 μg/m^3 in the mean annual concentrations of PM2.5 and PM10 over the previous years was associated with a 58% and 34% increase in COVID-19 incidence rate, respectively. Similarly, a 10 μg/m^3 increase of annual mean PM2.5 concentrations was associated with a 23% increase in all-cause mortality. An inverse association was found between NO_2levels and COVID-19 incidence and all-cause mortality. Similar evidence was reported by Mele et al. (2021) and Gujral et al. (2021) who monitored the incidence in three different neural networks for the cities of Paris, Lyon and Marseille as well as in Los Angeles and Ventura counties of California, respectively. The effect of the air quality on viral spread was demonstrated also by Sarawut-Sangkham et al. (2021) in the Bangkok Metropolitan region.

There is evidence that chronic and short-term exposure to air pollution exacerbates symptoms and increases mortality rates for similar respiratory diseases. This is consistent with early studies of COVID-19 mortality rates, but these results need to be confirmed and further consolidated by controlling for individual-level risk factors. Due to intense industrialization and urbanization, air pollution has become a serious global concern as a hazard to human health.

It is known that exposure to atmospheric particulate matter (PM) causes severe health problems in human and significant damage to the physiological systems. Hence, it is important to understand the adverse effects of PM in human health in their multidimensional nature. The review performed by Zhu et al. (2021) provided insights on the detrimental effects of PM in various human health problems including respiratory, circulatory, nervous, and immune systems along with their possible mechanisms of toxicity. Furthermore, the potential effects of short- and long-term exposure to atmospheric pollution on COVID-19 risk and fatality rates were well described in the analysis of the first epidemic wave in Northern Italy (Ho et al., 2021) or in the Catalan Tarragona Province in Spain (Marquès and Domingo, 2022). In the U.S., Zhou et al. (2021) found strong evidence that wildfires amplified the effect of short-term exposure to PM2.5 on COVID-19 cases and deaths, although with substantial heterogeneity across counties.

1.7. *Standardization issues*

Robotto et al. (2021) described a coherent preliminary approach to SARS-CoV-2 indoor and outdoor air sampling in order to overcome the evident lack of standardization. Three aspects are highlighted here in order to use this experience like a standard protocol adopted by the RESCOP Commission. First, quality and consistency to air sampling relies on the development of recovery tests using standard materials and investigating sampling materials, techniques, timing, sample preservation and pre-treatments. Second, in order to overcome the shortcomings of every single sampling technique, coupling different samplers in parallel sampling could be an efficient strategy to collect more information and make data more reliable. Third, with regards to airborne virus sampling, the results could be confirmed by simplified emission and dilution models.

2. Conclusions

Evidence coming from the current epidemiological and experimental research is expected to add knowledge about virus diffusion, COVID-19 severity in most polluted areas, inter-personal distance requirements and the effects of wearing face masks in different circumstances in indoor or outdoor environments. Moreover, the research outcomes might help to highlight the need for maintaining particulate matter concentrations at low levels, for many health-related reasons, besides whatever COVID-19-related effects. Indoor environment represents a challenge to cope with, as it is easier for SARS-CoV-2 to spread, remain vital and infect other subjects in presence of already infected asymptomatic or mildly symptomatic people in enclosed spaces. Effective preventive measures should be adopted in indoor public places and transportations, factoring effectiveness, epidemic activity, and cost considerations. Concerning special indoor environments such as hospital settings and nursing/retirement homes, further research is needed to determine warning thresholds of indirect indicators of contagion risk (i.e. CO_2), as well as to assess the viability and infective potential of SARS-CoV-2 present in the air of COVID hospitals, ambulances and emergency rooms.

Declaration of competing interest

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

Acknowledgments:

Authors are grateful to all the members of the RESCOP study group who are not listed among the authors of this paper and particularly to: Prof. Frank Kelly, head of the Global Centre of Air pollution research at Imperial College in London; Prof. Antonio Alcami from Severo Ochoa Center for Molecular Biology in Madrid; Prof. Darby Jack and Prof. Steven Chillrud from Columbia University, New York; Prof. M. Cristina Tirado von der Pahlen, director of the UCLA Institute for the Environment and Sustainability (Los Angeles); Prof. Cyril Gueydan, Mr. Oliveir Berten, Ms. Anne Botteaux from Université libre de Bruxelles (ULB), and Dr. Sandrine Bladt from Bruxelles Environnement; Prof. Antonio Marco Pantaleo (Imperial College, London); Prof. Francesco Salustri (University of Oxford); Prof. Igor Pereira (University of Rio Grande Do Norte, Brazil); Prof. Nguyen Tien Huy (University of Nagasaki, Japan); Prof. Riccardo Pansini (University of Dali, Yunnan, China), and Prof. Davide Fornacca (University of Geneve). Authors are also grateful to Daniel Lovegrove (Elsevier) for his support and advice in setting up the RESCOP Commission on Environmental Research journal.

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