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Learning from COVID-19: A roadmap for integrated risk assessment and management across shocks of pandemics, biodiversity loss, and climate change

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ABSTRACT

The COVID-19 pandemic demonstrated the fragility of international, national, regional, and local risk management systems. It revealed an urgent need to improve risk planning, preparedness, and communication strategies. In parallel, it created an opportunity to drastically re-think and transform societal processes and policies to prevent future shocks originating not only from health, but also combined with those related to climate change and biodiversity loss. In this perspective, we examine how to improve integrated risk assessment and management (IRAM) capacities to address interconnected shocks. We present the results from a series of workshops within the framework of the University of Zurich and University of Geneva. Initiative "Shaping Resilient Societies: A Multi-Stakeholder Approach to Create a Responsive Society". This initiative gathered experts from multiple disciplines to discuss their perspectives on resilience; here we present the key messages of the "Pandemics, Climate and Sustainability" thinking group. We identify a roadmap and selected research areas concerning the improvement of IRAM analysis capacities, practices, policies. We recommend the development of robust data systems and science-policy advice systems to address combined shocks emerging from health, biodiversity loss and climate change. We posit that further developing the IRAM framework to include these recommendations will improve societal preparedness and response capacity and will provide more empirical evidence supporting decision-making and the selection of strategies and measures for integrated risk reduction.

1. Introduction

The COVID-19 pandemic caused widespread disruption in health, economic and social systems worldwide. The impacts were severe, with effects cascading throughout society, posing a major challenge for risk management, response, and preparedness. In this article, we highlight some lessons learned and discuss potential benefits of adopting an integrated risk management perspective. First, the pandemic required fast response from systems unprepared for such speed. We observed different types of responses in all domains of society with varying degrees of success. These included lock-downs, economic subsidies, changes in labor dynamics and practices, more access to nature, and temporary greenhouse gases (GHG) reductions (Bates et al., 2020; Cooke et al., 2021; Diffenbaugh et al., 2020; Sills et al., 2020; Morand and Lajaunie, 2021; Forster et al., 2020). The pandemic resulted in a heavy toll in global population and societal processes. Until October 2023, COVID-19 caused over 6.8 million deaths (COVID-19 Dashboard, Johns Hopkins University). The United Nations Disaster Risk Reduction office calculated that, from the inception of the pandemic until 2021, COVID-19 pushed 119–124 million people into poverty and chronic hunger, and

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resulted in an equivalent of 255 million full-time jobs lost (UNDRR, 2021). These terrible effects demonstrated the fragility of international, national, regional and local risk management systems. It is therefore critical to learn from the successful practices and strategies adopted in some countries. Moreover, there is now an opportunity to drastically re-think and transform societal processes and policies to reduce the likelihood and impact of future shocks originating not only from health, but also from other ongoing crises that are expected to generate negative impacts, such as climate change and biodiversity loss. We already know that the window of opportunity to deal with these crises is narrow (e.g., Díaz et al., 2015; IPCC, 2014; IPCC, 2022) and that there is an urgency to be better prepared in the future (Le Quéré et al., 2021; McElwee et al., 2020; Santana et al., 2021).

The pandemic also highlighted that the interconnections between sectors of our daily life and the environment - that are essential for livelihoods and well-being - are also pathways for shocks to spread. These interconnections are essential to consider and understand in any attempt to enhance societal resilience and sustainability (Sandifer et al., 2015; Díaz et al., 2015). Indeed the environment is a major determinant of human health (e.g. Berry et al., 2018; Jones et al., 2008). This becomes even more evident as climate change, biodiversity loss, landscape change, shifts in species composition intensify various health risks, such as novel infectious diseases and cross-species viral transmission risk (Chowdhury et al., 2018; Moors et al., 2013; Carlson et al., 2022). Increase in numbers of domestic animals is a primary factor linked to biodiversity loss and is a source of a majority of virus emergence events. Overall death of humans from emerging viruses over the last century can be proximally linked to growth in animal-based food systems and population increase (Kock, 2022). Moreover, some of the underlying triggers of pandemics like COVID-19 are the same global environmental changes that drive biodiversity loss and climate change, namely land use change, agriculture intensification, overexploitation of natural resources (Daszak et al., 2020; Ortiz et al., 2021; Pörtner et al., 2021). Similarly, pandemics and other health system shocks can further trigger irreversible biodiversity loss and climate change, and are already being included in future scenario development (O'Neill et al., 2020). Importantly, pandemics, biodiversity loss and climate change are interconnected problems and predicted to become more intense/frequent (Lade et al., 2019; Folke et al., 2020; Lade et al., 2020; Lade et al., 2021; Ortiz et al., 2021). Evidence from a growing number of scientific studies can inform policies on these interconnected crises. For example, in a first-ever collaboration of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) and the Intergovernmental Panel on Climate Change (IPCC), leading experts confirmed that the climate and biodiversity crises are mutually reinforcing and can only be solved together (Pörtner et al., 2021). It is often argued that an integrated approach is fundamental to identify potential tipping points and risks across these systems, to improve preparedness, communication, mitigation and adaptation for more resilient societies (ibidem; Mitra and Shaw, 2023).

Integrated Risk Assessment and Management (IRAM) approaches have been called for as a solution for a better understanding of the systemic nature of risks. The concept of integrated risk management was originally developed in the late 1990 s-early 2000 s for organisations (especially in the private sector) to manage risks holistically and to promote a culture of prevention and preparedness (Meulbroek, 2002). Specifically, this concept was conceived to consider both financial and strategic uncertainties (Miller, 1992), and to go beyond the set of traditional (Meulbroek, 2002) insurable risks. This approach was then transferred to and adapted for complex risks. In this way, the need for integrated approaches to disaster risk management started appearing in international policies and documents. For example, the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNDRR, 2015) aims to: "Prevent new and reduce existing disaster risk through the implementation of integrated and inclusive economic, structural, legal, social, health, cultural, educational, environmental, technological, political and institutional measures that prevent and reduce hazard exposure and vulnerability to disaster, increase preparedness for response and recovery, and thus strengthen resilience" [p. 12] Progressively, integration has been conceptualized primarily as a combination of knowledge, methods, evidence, and data from different domains/disciplines (Mondino et al., 2023). These approaches have been applied in the mass-movement and flood disaster domain (to name but a few) and to address combined shocks. IRAM usually takes a holistic perspective through continuous assessment/monitoring of the risk situation and planning and implementation of protection/risk reduction measures, including measures to deal with residual risks (UNISDR, 2004; UNISDR, 2005; UNISDR, 2015; OECD, 2020). It considers different root causes and drivers of hazard, exposure, vulnerability and risk, and possible options to reduce risk ranging from containment/mitigation[2] measures, to emergency management and risk transfer. Moreover, it uses a variety of approaches for the assessment of risk and evaluation of options, borrowing methods from natural, engineering, economic, ecological and social sciences (Wouter Botzen et al., 2019). In addition to the identification of risk management options, other considerations can come into play when deciding about the implementation of integrated risk management strategies, such as equity, justice, acceptable risk levels, and impacts on the environment (Mechler et al., 2014; IPCC, 2014; IPCC, 2022). The need to promote such approaches has been clearly highlighted by COVID-19. Indeed COVID-19 cannot be framed exclusively as a health emergency and effective strategies to address it must encompass multiple domains, sectors, types of knowledge and evidence.

In this perspective, we discuss what research is needed to improve and promote IRAM systems to simultaneously address cascading effects of pandemics, climate change and biodiversity loss. We focus on these three planetary challenges because of the urgency to identify effective responses and solutions that consider synergies and trade-offs across risks. The paper grounds on the results of discussions of the "Pandemics, Climate and Sustainability" thinking group of the University of Geneva and University of Zurich (Switzerland). Initiative "Shaping Resilient Societies: A Multi-Stakeholder Approach to Create a Responsive Society". In the next sections, we describe the lessons learned during workshops and roundtables and present the options and recommendations for reforming risk assessment and management in light of future interconnected and systemic crises.

2. Lessons learnt from COVID-19 for IRAM

Surveillance for emerging and re-emerging pathogens as well as ensuring accurate information flow to the public are essential in preventing epidemics or pandemics and assessing their risk (Parihar et al., 2021). A recent review highlighted that throughout the history of pandemics, measures such as contact tracing, quarantine, and isolation have been incredibly effective in limiting outbreak severity (Weiss, 2022). Precedents include the 2003 SARS epidemic, followed by the 2009 H1N1 influenza pandemic, the 2014–2016 Ebola outbreak in West Africa, Zika, and other disease outbreaks, including another new coronavirus responsible for the Middle East Respiratory Syndrome (MERS). Further, while vaccines are thought to be an irreplaceable defense, their development and distribution in time to curb an epidemic has seldom been witnessed. Preparedness thus means to know the origins, functioning, impacts, and key drivers of a pandemic, or other shocks. Importantly, preparedness also relates to other system features, such as

[2] Measures can be distinguished between containment and mitigation (Ferguson et al., 2020). The former attempt to circumscribe hotspots of the infection and through an aggressive set of quarantine measures and lockdowns of activities and services avoid the spread throughout a region or a country. In the latter, a set of differential measures is taken, focusing on avoiding mass gatherings and situations and activities that constitute a high risk of rapid virus transmission.

widely available and affordable healthcare, high levels of education, safe and secure work, and trust in authority (Collins, 2009).

To date, the core components of pandemic preparedness plans consist broadly of (i) surveillance to detect pathogens, (ii) data collection and modeling to predict spread, (iii) improvements to public-health guidance, public preparedness, education and communication, and (iv) the development of therapies and vaccines (Maxmen, 2021). Low levels of preparedness mean that, for example, in 2018, six out of the twenty-seven European member states did not include epidemic/pandemic risks in their National Risk Assessments (EC, 2017). Even among the countries that had preparedness plans, the risk has been so far generally underestimated or action plans were often not up to date (Zambon, 2021). For instance, in the UK a scenario planning exercise for a pandemic influenza outbreak was organized in October 2016 - as an exercise called Cygnus - and resulted in a stark warning: “UK preparedness is currently not sufficient to cope with the extreme demands of a severe epidemic” (Horton, 2020). Nonetheless, insufficient action was undertaken since, such that (at the time) UK government Chief Scientific advisor stated that they “[…] learnt what would help, but did not implement those lessons” (*ibidem*: 21).

After the onset of COVID-19, there was an unprecedented momentum in research aimed at understanding the pandemic and its risks. Medical research concerned discovery of the characteristics of the new virus, infection transmission modalities, identification of appropriate treatments, and development of vaccines (Menoni and Schwarze, 2020). Other research focused on determining the exact origin of the COVID-19 virus, and how it is related to human exposure to (novel or unknown) pathogens and disease vectors, trade of wild and domestic animals, and the connections to biodiversity loss and climate change (for updated overviews see International Union for the Conservation of Nature, IUCN: https://portals.iucn.org/library/node/49880 and IPBES: https://ipbes.net/pandemics). To enable this momentum, public and private sector organizations around the world provided dedicated funding in record time. Open access COVID-19 databases and research were promoted and publications were made available as open source on-line.

Therefore, it seems wise to maintain or even increase this research momentum, and examine its continuously evolving focus in light of new research needs. To this aim, we reflect on the role played by risk science, that focuses on risk analysis, management and governance, and is grounded in different disciplines in the natural, social and economic sciences (for a review see UNISDR, 2004; Aven and Bouder, 2020). Evidence in risk science highlights the importance of investing in risk prevention and preparedness. As the global risk landscape is undergoing rapid and profound changes, with a trend for more severe and complex impacts that cascade through social, economic and environmental systems, risk science approaches should thus be flexible and operate more innovatively and collaboratively to address increasing levels of complexity (Ortiz et al., 2021; Aven and Bouder, 2020), and to effectively address combined shocks. Whilst Hewitt and Burton (1971) noted already a half century ago the need to shift natural-hazard research and practice from a single-hazard approach towards a systematic cross-hazard approach (Ward et al., 2022), data availability and difficulties in quantification make it still very difficult to apply systemic, integrated, and multi-risk frameworks.

So far, IRAM pandemic-related research expands beyond the above-mentioned preparedness plans to include other aspects of risk management, namely the type of risk, the assessment of impact and risk propagation, the response and management support system in place, recovery strategies, and whether these aspects are considered in an integrated (and even systemic) approach. Research areas include, e.g., (i) COVID-19, climate, and biodiversity (e.g. Ortiz et al., 2021; Aven and Bouder, 2020; Pelling et al., 2021b; Pelling et al., 2021a; OECD, 2020); (ii) decision support systems, differential impact and vulnerability assessment (e.g. Chatterjee et al., 2020; Shaw, 2020; Menoni and Schwarze, 2020; Leonelli, 2021; Aven and Bouder, 2020); (iii) risk perception, preparedness and behaviours (e.g. Siegrist and Bearth, 2021; Siegrist et al., 2021; Mondino et al., 2020; Dryhurst et al., 2020; Selby et al., 2020; Di Baldassarre et al., 2021; Friemel and Geber, 2021; Schneider et al., 2021; Diffenbaugh et al., 2020; Chatterjee et al., 2020; Hale et al., 2021); (iv) risk communication (e.g. Menoni and Schwarze, 2020; Chatterjee et al., 2020; Selby et al., 2020; Hanson et al., 2021; Friemel and Geber, 2021; Wu et al., 2021a; Fearnley and Dixon, 2020); and (v) integrated risk policy, finance, governance, and resilience (e.g. OECD, 2020; UNDRR, 2021; Wu et al., 2021a; McElwee et al., 2020; Hale et al., 2021).

An increasing number of publications argue that a more holistic, systemic and integrated approach to risk is critically needed. It should consider hazard, vulnerability, exposure, and capacities together, and clarify their complex interactions (UNDRR, 2021; for a systematic literature review see Mitra and Shaw, 2023). Some authors maintain that integrated risk science will need to be re-imagined with a much broader scope and reach, working collaboratively not only across health, biodiversity and climate risks, but also across different types of knowledge, disciplines and sectors, e.g., the private sector (Aven and Bouder, 2020). Indeed, the adoption of a more systemic and integrated approach in risk management has been already extensively advocated (e.g. GAR 2022). As mentioned in Section 1, this approach aims to identify interactions across system elements, address the underlying causes of crises, and tackle combined shocks concurrently (UNISDR, 2015). For example, compounding effects may occur when disaster shelters and evacuation centers (e.g., for flood or extreme events) designed to protect individuals from catastrophic events (e.g., a second flood) can increase COVID-19 transmissibility (Pelling et al., 2021a; Richard et al., 2021; Kamrujjaman et al., 2021; Mantyka-Pringle et al., 2015). COVID-19 transmission risks can also be increased by inadequate water, sanitation, and hygiene infrastructures or when combined sewer systems overflow during floods (Pelling et al., 2021b).

Yet, despite knowledge of feedback and/or interaction among the different crises, there is limited integration especially of quantitative data (Mondino et al., 2023). For example, a risk-oriented approach has long been used to understand climate and atmospheric dynamics, but the same approach based on quantitative risk assessment has been used less frequently in research about biodiversity loss. However some drivers of biodiversity loss (e.g. mostly land use change) were taken into account in assessing overall biodiversity risk in the shared socioeconomic pathways (Pörtner et al., 2021) (Mantyka-Pringle et al., 2015).

Newer studies assess risks generated by interrelated processes such as climate change, biodiversity losses, and zoonotic diseases. For example, Keesing and Ostfeld (2021) assess the impacts of biodiversity loss on zoonotic diseases. Also, risk values may be put against some of the coarse risk factors, e.g. changing demographics, air travel, land use change, climate change, biodiversity loss, agriculture (especially animal based). Together with risk attribution, much more precise risk analysis can then lead to the identification of risk reduction options.

In Fig. 1, we provide an overview of conceptual linkages between pandemics, biodiversity loss, and climate change. The figure includes examples of the connections between the shocks and the processes of pandemics, biodiversity loss, and climate. In Fig. 2 we provide an overview of potential solutions for individual interactions and for a novel type of IRAM. For example, nature-based solutions (NBS) are an example of solutions that can contribute to jointly address the three crises because they simultaneously provide human well-being, ecosystem services, resilience, biodiversity benefits and risk reduction (e.g. Seddon, 2022). Another example are the positive indirect effects of pandemics on biodiversity, e.g., more biodiversity when pandemics restricted human presence in wildlands.

To contribute to the debate about IRAM capacity development for current and future shocks, recovery paths, and to ultimately build more sustainable and better prepared societies and ecosystems, we present the key insights of a stakeholder consultation process. It was launched by the University of Geneva and University of Zurich in the year 2020. These insights emerged in the framework of the initiative "Shaping

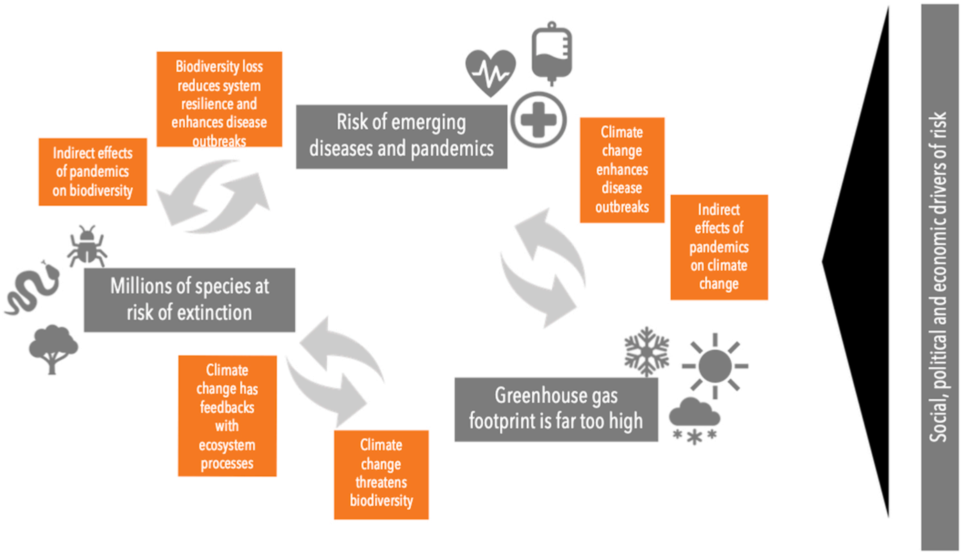

Fig. 1. Conceptual linkages between pandemics, biodiversity loss, and climate change as shocks to the Earth and human systems, i.e. the overarching reason for developing better IRAM. Grey Boxes exemplify the shocks from pandemics (e.g., more than five new diseases emerge in people every year, any one of which has the potential to spread and become pandemic), biodiversity loss (e.g., land-use change, agricultural expansion and intensification, trade and consumption, disrupts natural interactions, increases contact among wildlife, livestock, people, and their pathogens) and climate change (e.g., climate change results from large emissions of CO2 resulting from human activities locally and globally). Orange boxes exemplify linkages between health and biodiversity (e.g., fragmented ecosystems and human encroachment lead to zoonotic disease outbreaks), between biodiversity loss and climate processes (e.g., ecosystem functions may reduce climate effects through for instance carbon sequestration, regulation of water cycles, energy fluxes; climate change has been implicated in changing species ranges, physiology and extinction), and between climate change and emergence of diseases and pandemics (e.g., climate change has been implicated in disease emergence as well as reducing human ability to be resilient to disease; reduced human global transportation resulted in lower emissions during the pandemic).

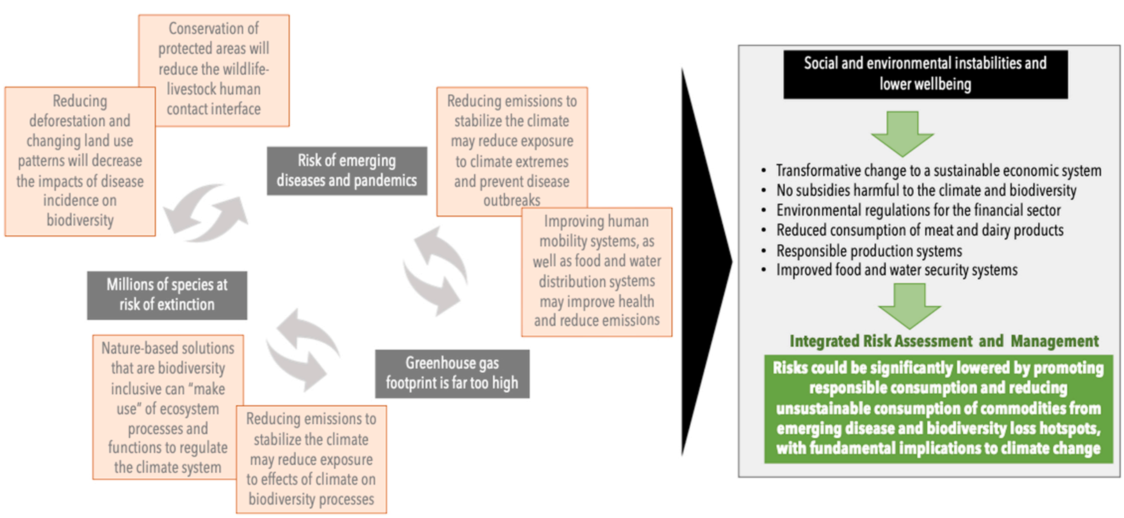

Fig. 2. Potential solutions and the emergence of a new IRAM, which focuses on new ways to deal with the impacts of the combined shocks and how solutions at the interface between disease, biodiversity, and climate change could reduce social instability and improve well-being of society and nature.

Resilient Societies: A Multi-Stakeholder Approach to Create a Responsive Society" and of two roundtables organized respectively at the United Nations Economic Commission for Europe (UNECE) Regional Forum and at the United Nations (UN) High Level Political Forum on Sustainable Development.

3. Thinking about pandemics, climate and sustainability to "Shape Resilient Societies"

Between September 2020 and July 2021, a series of workshops brought together more than 60 stakeholders including scientists and policy-makers to evaluate and future-proof local, national and international response mechanisms, policies and strategies. Here we focus on the activities of the "Pandemics, Climate and Sustainability" thinking group, which included representatives from national governments, research institutions, the International Union for the Conservation of Nature (IUCN), United Nations Environment Program (UNEP), World Health Organization (WHO), World Meteorological Organization (WMO). This group was tasked with discussing the interconnections between COVID-19, biodiversity loss, climate change in the context of system resilience.

The thinking group focused on setting the stage of what is known from a systems perspective on the interactions between pandemics, biodiversity loss and climate change. Some of the key questions leading the discussions included: i) what are the key drivers, stressors and vulnerabilities in the health, biodiversity and climate systems?; ii) how have biodiversity and climate systems acted in relation to the pandemic?; iii) what are the opportunities for tackling multiple shocks concurrently?; iv) how can we achieve `post` pandemic resilient societies? The thinking group focused on setting the stage of what is known from a systems perspective on the interactions between pandemics, biodiversity loss and climate change.

Participants agreed that there is still a need to better understand health, biodiversity and climate processes independently. They also saw the need to link them through their direct, indirect and cascade effects over time and across scales and to identify common root causes. Then, they discussed opportunities and needs for tackling concurrent shocks. The final topic was what could be done to achieve a post COVID-19 resilient society. Core issues mentioned in the discussions included the need to better understand multiple risk exposures and its drivers, to improve analysis of social vulnerability and heterogeneity especially in social systems, and to identify transdisciplinary response mechanisms to address multiple crises. For example, nature-based solutions have been mentioned as measures capable to reduce simultaneously the impacts of multiple risks, including climate, health and biodiversity, and to generate multiple co-benefits for nature and society (see also Fig. 1). Drawing on the "Pandemics, climate and sustainability" thinking group key insights, in the subsequent sections we present a roadmap with four pathways for IRAM research and practice in the health, climate and biodiversity systems (Workshops presentations, recordings, and minutes are available upon request).

4. Road map for IRAM research

4.1. Developing robust data systems at international, national, and local scales

Data has become crucial for efforts to monitor and contain viral spread, while enabling a continuity of critical societal functions. In a very short time, and under great urgency, actors from different sectors (e.g. public health, legal and digital technologies) came together to build an effective response. Thus, it is important to improve data quality and clearly identify redundancies to generate robust evidence for recommendations. However, data is of different qualities for the different aspects of IRAM. For environmental processes, data on health (at least in the global north) was readily available, and models and science developed quickly. Strong inequalities emerged in data quantity due to, among others, the disparity of data collection protocols (e.g., https://coronavirus.jhu.edu/map.html; https://www.emdat.be/). For example, for the understanding of pandemic related social processes, data was less available (but see e.g., https://publico.community/). More robust data, innovative models and experiments are necessary to examine behavioural data, and the interconnections between environmental, social, and public health systems.

Moreover, as the combined processes of health, biodiversity loss and climate change occur at different scales, the data need to reflect such scales. For this, data redundancy and quality are relevant when it comes to design response mechanisms. IRAM approaches should draw from robust data collected by public and private organizations at international, national, and local levels at different scales and should aim to conduct robust risk assessment and to measure different processes and indicators. However, two issues emerge. First, the interoperability between different databases is key for cross-scale analysis and cross-disciplinary analysis, especially between epidemiology (e.g., virus spread), biodiversity (e.g., loss of natural habitat in cities) and climate (e.g., air quality). In this regard, for instance, the World Environmental Situation Room (WESR, https://wesr.unep.org/) offers promising services to improve cross-analysis between biodiversity and climate. Second, data is often of insufficient quantity, coverage, granularity, and quality to be effectively used in IRAM. Novel ways to populate and use these databases need to be identified, e.g., by involving citizens and other stakeholders engaged in IRAM processes.

One promising avenue is citizen science. It offers an opportunity to include the capacities of many to deal with future environmental, societal, and epidemiological shocks by not only collecting data (or crowdsourcing), but also by co-designing important research questions (through participatory science), analyzing existing data (through distributed intelligence), and building bridges among different citizens for instance, smartphone-users, researchers, journalists, enterprises, and executive bodies (through collaborative science). For example, better data availability on behavioral responses, socioeconomic vulnerability and inequalities in post-COVID-19 recovery collected through citizen science could inform policymaking to better prioritize social vulnerability reduction and promote just decision making processes. A multiscale approach, collecting data across scales and sectors, is fundamental to analyze the coupling of environmental and social processes, and to examine synergies, trade-offs, and spillover effects at the crossroad between climate, health and biodiversity systems.

Nevertheless, extensive data collection alone is insufficient to support decision making processes. The pandemic cannot be explained by a virus *per se* but rather because of preexisting risk conditions and management policies. Disasters generally reveal that without reducing inequality, poverty, and exclusion, those most affected will see their risk increase (Alcàntara-Ayala et al., 2021). In this context, sensible decisions must often be made without extensive data or under uncertainty (Pelling et al., 2021). Moreover, it is essential to consider that risk assessment and management is not a technocratic, scientific endeavour disconnected from everyday policymaking processes. The latter, very often, have more bearing on risk outcomes than the scientific understandings of the issues in question (Hewitt, 1983; Collins, 2009; Lavell and Maskrey, 2014; Nightingale et al., 2020). Linking knowledge to decision making is not a linear and one-way process, but it rather requires new approaches to the intersections of knowledge and power which can enrich disciplinary engagements with the politics of interconnected crises (Mahony and Hulme 2018; Mahony, 2020). Indeed, often power is attributed to the 'evidence' to avoid the impression that human agency has a role in policy-formation (Donovan 2017; Gaillard, 2021). This terminology is problematic especially when evidence is uncertain, and the policy is most likely to be based on inference from the uncertain evidence (McGowran and Donovan, 2021). Therefore, consideration of development of robust data systems must be accompanied by awareness of power dynamics related to data collection and generation of reliable evidence.

4.2. Improving integrated risk analysis capacities

The improvement of integrated risk analysis capacities, especially but not exclusively in the environmental sector, is a priority and could benefit from the adoption of interdisciplinary approaches. Policy decisions during COVID-19 have been based primarily on health data such as incidence, case fatality ratio, vaccination rate, etc. There are gaps in forecasting social, economic, and psychological consequences of mitigation and containment measure implementation, benefits and costs. Linked to that, there are often difficulties in integrating evidence from different disciplines, e.g., looking at epidemiological alongside economic models, or modelling the social or psychological effects of different policy choices about containment and mitigation measures (Mulgan, 2022). Especially the integration of quantitative data on social behaviours in biodiversity, climate or pandemic modelling remains one of the key gaps (Mondino et al., 2023; Di Baldassarre et al., 2018).

Therefore, better decision support tools to analyze, assess and manage the social and economic impacts of systemic crises on given sectors, including those that are not necessarily on the frontline in risk and emergency management (e.g., education or business sector) are needed. Further, risk analysis capacities can only be improved when the most vulnerable groups and those most affected by the short-, medium-, and long-term consequences of these crises are identified, and adequate measures are planned and acted upon. Finally, we need to develop scenarios and analyses of system capacities and performance to face different crises, including the health effects of the climate and biodiversity crises. Analyses should consider risk exposure and its drivers, and focus on the spillover effects of the health, climate and biodiversity crises, for instance, effects on migration. Regarding interrelationships between health care capacity, society and economy, we need to identify the non-intended consequences and the side effects of mitigation and containment measures. This includes dealing with trade-offs and synergies between health, economic, social and environmental measures to reduce risk. If synergies between environmental and health improvements are evident, trade-offs between the health and economic dimensions are one of the critical aspects that generated diverging views on COVID-19 risk management decision making. To address these trade-offs, the development of interdisciplinary and transdisciplinary approaches for IRAM is necessary. These approaches should consider that the effective implementation also involves power dynamics that can significantly affect the decision-making processes and distribution of impacts (Donovan, 2021).

4.3. Improving science-policy advice systems

Government capacities to weight scientific evidence, understand it, synthesize it, use it to support effective decision making and communicate it are often limited because politicians or civil servants have little familiarity with results or time to dedicate to analyze and synthesize results. Further, decision makers may have views that reflect the interests of specific socio-economic groups. Moreover, often time pressure is high and decisions are urgent (Funtowicz and Ravetz, 2013; Funtowicz and Ravetz, 1993). During the COVID-19 pandemic, scientific advice for policy decision making has revealed strengths and weaknesses of existing models to provide effective decision support and communicate it. In the thinking group discussions, we identified five aspects that need further attention.

First, there is a need to build a system to better prevent and disclose the dissemination of statements that are not sufficiently supported by evidence. It is fundamental that any disseminated recommendations (by scientists, public agencies, or indeed any source) are based on robust evidence. Linked to this, fast evidence review (i.e., fact checking) processes are needed to deal appropriately with the inconclusive evidence and divergent scientific conclusions that naturally can occur early in the process of a scientific investigation of a novel situation (Norberg et al., 2022).

Second, the co-design of effective multi-stakeholder strategies for crisis management and for a robust science-policy interface should be promoted. It is important to avoid for example that decisions based on policy makers judgements/responsibility are erroneously presented as scientific evidence. Scientific statements typically come with an indication of confidence, which can be quite limited sometimes. For instance, scientific evidence about the health and environmental impacts of certain technologies often does not imply thresholds. The identification of safety thresholds implies a value judgement and a responsibility towards the people or generations affected. Presenting thresholds as scientific may help making impacts acceptable to the population. However, in the long run, this approach may be detrimental to the credibility of science in our society.

Third, policy makers need to develop flexible systems and engage in long-term dialogue with scientists to openly discuss, e.g., the criteria to assess the effectiveness of decisions (e.g., on IRAM measures) and what kind of evidence is required to support decision making processes. More precisely, not only quantitative but also quantitative and qualitative evidence integration should be promoted. The results of a scoping review on COVID-19 integrated risk management (Mondino et al., 2023) reveal that a key component of IRAM strategies is the adoption of co-production approaches that bring a plurality of knowledge sources, types, and stakeholders together for policy, decision making or problem-solving purposes. These approaches also integrate qualitative and quantitative evidence and have proven effective to co-define policy objectives for long term crises like COVID-19 (see also examples reported in Section 4.1). Thus, new methodologies to promote formal involvement of residents, civil society organisations, and other stakeholders within the management strategies should be developed and tested.

Fourth, IRAM should inform and support transversal policymaking and policy instruments design, implementation and monitoring. Citizen science can support this effort by offering online platforms for improving public participation in reporting hazardous issues and planning responses to identified risk. More generally, the COVID-19 pandemic has underlined the need to partner with stakeholders at the local level and communities in pandemic preparedness and response to enable trust-building among stakeholders, which is key in risk management (for an overview see Tan Y et al., 2022).

Fifth, policy objectives should be identified based on stakeholder engagement processes that involve not only scientists but also members of the civil society and representatives of different sectors. For example, in the case of COVID-19 there has been a debate in many countries over the relative weight of the objective of containing the number of deaths versus the objective of preserving economic growth. Eventually, several countries during COVID-19 gave priority to the first. However, in the case of climate, priority has been so far attributed primarily to the economic motif over the public security motif. Yet, the dichotomy health-economy is problematic and can lead to decision stalemates or conflicts, rather than supporting decision making processes. Participatory approaches to co-define priorities in policy objectives for long term crises like COVID-19, climate change and biodiversity loss should be developed and tested. For instance, Ekenberg et al. (2021) involved relevant stakeholders from various sectors, including policymakers, the private sector, academia, civil society, banks, and representatives from local communities to assess different pandemic mitigation measures. Multi-criteria decision support tools have then been used to co-identify priorities. Another example is Margherita et al. (2021). They involved a hospital nurse, a sociologist, a psychologist, a civil engineer, an economist, a public manager, and two engineers to develop a framework for modelling activities, actors, and resources coordination in an epidemic scenario. With an iterative process, the participants co-designed a framework (first stage) which was then submitted to the various experts for review (second stage). In the third stage, the feedback was incorporated into an epidemic scenario to support decision making. In this way, experts and practitioners from the economic and health sector worked together to co-develop new solutions. These examples clearly show that bottom up and transparent decision-making structures should be open rather than centralised and science led (Donovan, 2021; Donovan 2017; Mahony, 2020; Mahony and Hulme, 2018).

4.4. Improving integrated risk management strategies and institutional capacity

More effective IRAM strategies could be achieved through a combination of three aspects. First, establishing and promoting cross-sectoral legislation and mechanisms at the international, national, and municipal scales for resilience to systemic crises across different spatial and temporal scales. For example, the compound effects between COVID-19 impacts and climate risk highlight the need and opportunity for targeted investment in basic services (e.g., wash systems) to address vulnerability across pandemic, public health, climate change, biodiversity, and potentially other risks (Pelling et al., 2021b).

Second, risk management models should be preventive rather than response-focused, as well as cross-sectoral. Improved coordination and partnership between the public and private sector is a critical gap to fill together with the promotion of social entrepreneurs at the local level to foster community resilience to multiple threats. To increase disaster preparedness, novel financing opportunities including new forms of responsibility sharing between the public and private sector should be identified.

Third, maintaining the political commitment and institutional capacity to promote preparedness between crises also deserves attention. Several countries (e.g., Italy, UK) make employ not only task forces to provide advice during the emergency phase but also use preparedness commissions to revise existing national risk management strategies (Horton, 2020). It is of critical importance that these efforts are continued, are further developed in the lulls between crises, and are supported in the long term with particular attention to biodiversity, climate, and health crises.

The example of IRAM strategy for improved public health, better air quality and climate change mitigation was mentioned as a good practice. Indeed, most strategies for reducing greenhouse gas emissions may also decrease emissions of health-damaging air pollutants and precursor species, including NO2 and particulate matter. Nemet et al. (2010) argued long before the onset of the COVID-19 pandemic that air quality co-benefits have the potential to enhance incentives for cooperation by engaging actors that are averse to the costs of climate policy or unmotivated by avoided climatic damages. This, in their view, is because air quality co-benefits are relatively local and near term, and are health related. (See also Wu et al., 2020; Rohrer et al., 2020; Woodby et al., 2021; Lai et al., 2021; Rebuli et al., 2021; Watzky et al., 2021). Moreover, evidence of strong links between climate change and the exacerbation of respiratory and cardio-pulmonary diseases is adding even more compelling reasons for a joint strategy for better air quality and climate change mitigation (Rohrer et al., 2020; Zhou et al., 2021; Wu et al., 2021b; Xu et al., 2020).

Another example of integrated approach is the development of joint biodiversity and climate plans at regional or national level. This can contribute to foster policy synergies by linking NBS policies to preventative healthcare policies and to green infrastructure, transport and mobility policies (Scolobig et al., 2023).

5. Conclusions

Worldwide, the low level and heterogeneity of preparedness to face the COVID-19 crisis had several side effects further exacerbating the negative impacts of the pandemic. While there was acknowledged failure of many governments to invest in preparedness measures (Response, 2021), the pandemic has the potential to be a window of opportunity to transform risk management systems. Indeed climate, biodiversity and health shocks are global challenges that if not met, pose risks to all citizens. Furthermore, responses need to be integrated and at system level. While the linkages between these crises start to be widely recognized by science, they are still often considered in isolation in applied scientific research, policy and practice. Applied scientific research is further needed to comprehensively answer open research questions about the biodiversity, health and climate nexus, as well as about engaging society in developing and implementing solutions to tackle these crises. Importantly, it is critical to consider that the conceptualizations of this nexus are embedded within the politics and legitimacy of knowledge (Nightingale et al., 2020). Not only data, but also values, normative commitments, experiential and plural ways of knowing need to be considered. For truly transformative change to gain traction, human, economic and institutional resources must be dedicated to open deliberative spaces and to change knowledge systems, e.g., by allowing plurality of knowledge types to be included (ibidem; Gibson et al., 2016). Hence, we call upon citizens, epidemiologists, biologists, geographers, social scientists, economists, policy makers, risk experts and managers to work together, fill knowledge gaps on the interlinked factors producing increased vulnerabilities and to develop adequate IRAM strategies. As a result, IRAM advanced knowledge and empirical evidence will improve societal preparedness and the ability to assess and manage risks of pandemics, climate change and biodiversity loss.

Ethical approval

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CRediT authorship contribution statement

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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.

Data availability

Data will be made available on request.

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Consent to Publish

All authors have read and agreed to the submitted version of the manuscript **Competing Interests**: The authors declare no competing interests.

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