



# Risk management for pandemics: a novel approach

“Hindsight is 20/20” English proverb

Ian G. McKinley<sup>1</sup> · Julia M. West<sup>1,2</sup> · Susie M. L. Hardie<sup>1,3</sup> 

Received: 26 November 2020 / Accepted: 24 June 2021 / Published online: 9 July 2021  
© The Author(s), under exclusive licence to Springer Japan KK, part of Springer Nature 2021

## Abstract

The impacts of the current COVID-19 pandemic illustrate the global-level sensitivity to such threats. As understanding of major hazards is generally based on past experience and there is a lack of good historical precedents, approaches and models currently employed to assess risks and guide responses generally lack transparency and are often associated with huge, unspecified uncertainties. Fundamental challenges arise from the strongly coupled nature of the impacts of a pandemic (i.e. not only on health, but also on the entire socio-economic infrastructure) and their long-term evolution with recovery likely to take many years or, potentially, decades. Here, we outline experience gained in risk assessment within the nuclear industry, which has experience facing similar challenges (assessing long-term impacts in a strongly coupled technical system subject to socio-economic constraints), and assess options for knowledge transfer that may help manage future pandemics and other high-impact threats.

## Introduction

Although risk management is a reasonably well-established practice in many technical and commercial fields (e.g. Sodhi, et al. 2012; Allen, et al. 2006; Oliver, et al. 2004; Rubio and Bochet 1998), its application is inherently limited when it comes to consideration of emerging and global-scale hazards (Aven 2015; Eling and Schnell 2016; Flage and Aven 2015). This is clearly illustrated by the socio-economic chaos caused by the current COVID-19 pandemic (e.g., Baldwin and Weder di Mauro 2020), which was not only a well-recognised threat (Cheng et al. 2007; Fan et al. 2018),

but one that had been presaged by a number of similar infectious diseases in recent decades (McCloskey et al. 2014; Fan et al. 2018). With the benefit of hindsight, it can be seen that many threat reduction/containment measures were poorly handled (Fan et al. 2018), but a more fundamental problem is the lack of a global risk management approach so that, even now, responses are implemented on an ad hoc, local/regional/sector basis without any structured international coordination, leadership or mobilisation of resources (Aven 2015; Gossling et al. 2020; Yarovaya et al. 2020). Furthermore, as Keogh-Brown et al. (2010), noted, “the current pandemic has not removed the threat of a more virulent avian flu pandemic in the near future. [...] the importance of pandemic planning is plain”.

Better coordination is constrained by limitations in the associated risk assessment methodology (Bedford et al. 2020; Oehmen et al. 2020; Wang et al. 2020), which is primarily focused on direct health impacts and, even then, it is not able to respond to the novel and changing technological and socio-political boundary conditions. This is unsurprising: events like pandemics produce impacts with multiple positive and negative feedback loops and are thus inherently chaotic, so that the smallest uncertainty in starting conditions or specific responses can result in huge differences in resultant impacts. Mathematical models used are only as good as the assumptions that form their basis and thus,

Handled by Siddharth Sareen, University of Stavanger, Norway.

✉ Susie M. L. Hardie  
schwarzhara@vol.at

Ian G. McKinley  
ian@mckinleyconsulting.ch

Julia M. West  
julia@west-consult.com

<sup>1</sup> McKinley Consulting, Badstrasse 20B, 5408 Ennetbaden, Switzerland

<sup>2</sup> West Consult, Nottingham, UK

<sup>3</sup> Schwarz Hara Consult, 6774 Tschagguns, Vorarlberg, Austria

in many if not most cases, are based on educated guesses (Boccaletti et al. 2020; Ferguson et al. 2006; Wang et al. 2020). Here, the lack of sufficiently analogous precedents for the present pandemic limits not only empirical or heuristic approaches, but also alternative analytical or model-based methods, due to the lack of any way of validating the resultant output (Fakhruddin et al. 2020). Thus, over-interpretation of quantitative analyses can worsen problems and add to the confusion of both decision makers and the general public (McDermott and Surminski 2018).

Given the magnitude of impacts of major pandemics—on the scale of fractions of Gross World Product over timescales of years to decades—there is a clear need to develop better ways to manage the associated risks (Trump and Linkov 2020). However, given the issues noted above, there is little hope that methodologies can be based on the tools normally used for social/economic modelling.

Here, we suggest an alternative approach that focuses on developing a holistic overview and summarises the basis for decision-making in a user-friendly, visual manner, based on the techniques and tools developed in the nuclear industry. This may offer a better chance of success for assessment of risks and their subsequent management, also providing an aid to communication of decisions that may help to avoid the mixed messages that are still rife, even 18 months after the threat was recognised. Specifically, we discuss tools used for safety assessment of geological waste disposal, where prediction and quantification of scenarios (and the associated large uncertainties to be managed) develop over millennia, within complex natural and engineered environments that are inherently impossible to characterise in detail (Makino 2009, 2011; McKinley et al. 1997). These alternative approaches provide a different perspective to those used to guide the very diverse national response strategies that have

been implemented, capturing the true complexity and coupled processes characteristic of natural systems in a visual manner that facilitates required multi-disciplinary communication and synthesis. In doing so, this allows improved assessment of pandemic risks and counter-measures to reduce their impacts and/or probability of recurrence.

## Problem specification

The first issue to be addressed is threat recognition. Although any assessment of global health hazards over the last century or so will clearly identify pandemics as a serious threat (e.g. Bloom and Cadarette 2019; Fan et al. 2018; McCloskey et al. 2014), this contrasts with the low priority given to preventative measures. As shown in Table 1, the mortality rate can be very high and, potentially more significant, a large fraction of the global population can be infected leading to major secondary impacts as discussed further below.

Despite a number of international response plans being developed after serious epidemics in recent decades (e.g., Ebola virus disease (EVD), SARS-CoV), these were not prioritised prior to identification of the COVID-19 threat. Even at a national level, planning was generally poor—with the exception of some countries where response infrastructure from such previous epidemics was still in place, reflecting risk awareness based on past experience (e.g. South Korea, Hong Kong and Japan). Problems could be attributed to either socio-political short-termism or lack of understanding of the wider impacts of a pandemic, but certainly reflect the lack of holistic risk management strategies to support key policy decisions.

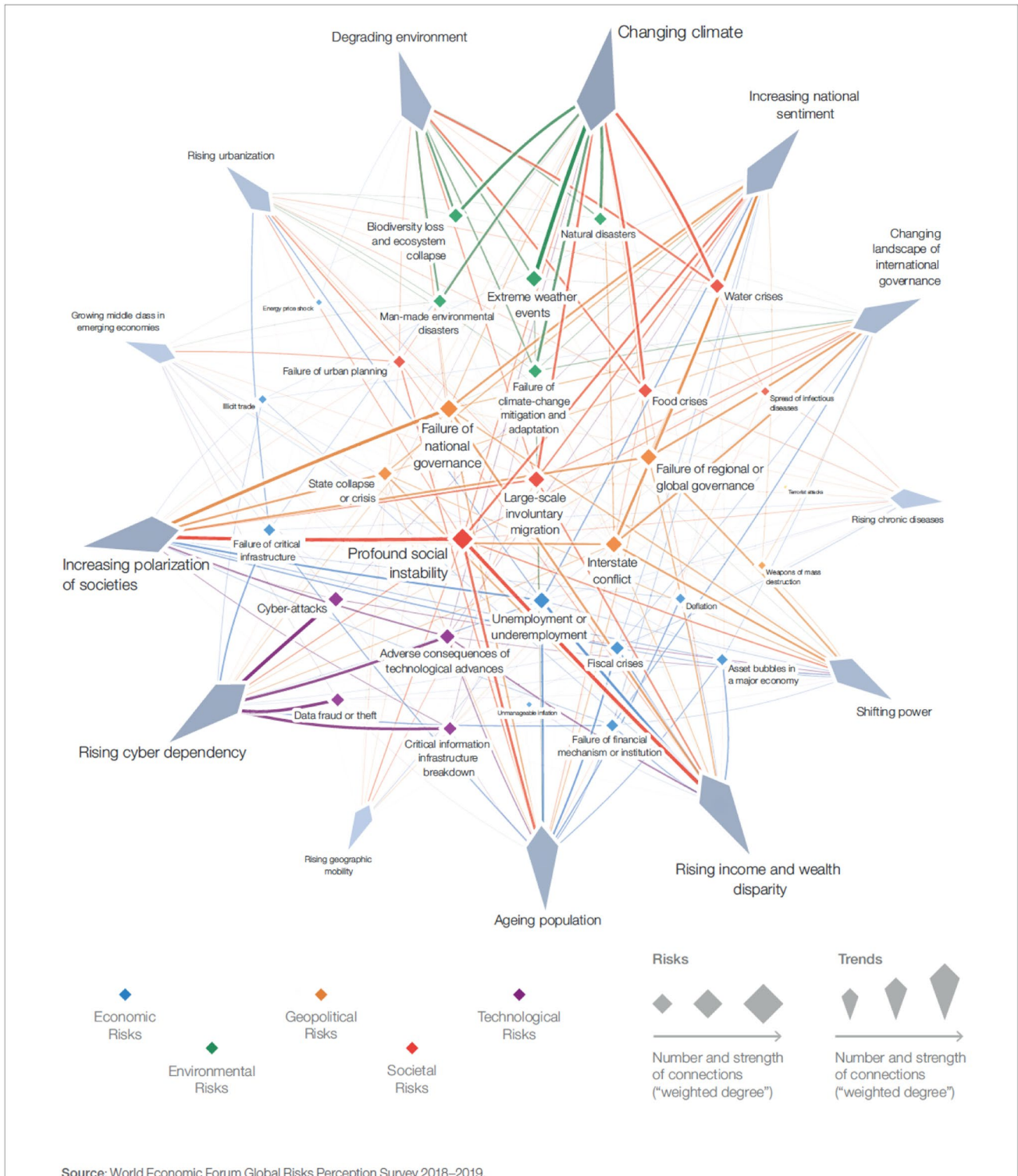
The disconnection between real threats and those perceived by key decision makers is highlighted by the

**Table 1** Causes of human death: some examples (data from World Health Organisation (WHO), Centers for Disease Control and Prevention, USA (CDC) and United Nations Office of Drugs and Crime)

Description	Timeframe	Deaths	Comments
Malaria	Recorded history	Many millions throughout history 2000—839,000 2018—405,000	In 2018 estimated 228 million cases worldwide
H1N1 virus	1918–1919	Estimated 20–50 million worldwide	Estimated that one third of world population infected
H3N2 virus	1968	Estimated 1–4 million worldwide	
Car accidents	21st Century	1.35 million per annum worldwide	Between 20 and 50 million people injured per annum worldwide
Alcohol abuse	21st Century	Estimated 3 million per annum worldwide	Estimated 237 million men and 46 million women suffer alcohol-use disorders worldwide
Drug abuse	21st Century	585,000 worldwide in 2017	35 million people suffer drug related disorders worldwide
Antimicrobial drug resistance	2019	Estimated 700,000 per annum	Estimated 10 million deaths each year by 2050
COVID-19	2020–2021	3,758,560 deaths worldwide (10 June 2021)	Total 174,061,995 confirmed cases worldwide (10 June 2021)

assessments of the greatest risks to the global environment performed by the World Economic Forum (WEF): Fig. 1 provides an example from 2019. In this figure, major global

trends are identified and these are related to key risks, broken down into the categories: economic, environmental, geopolitical, societal and technological.



**Fig. 1** WEF perceived risk identification (WEF 2019, The Global Risks Report 2019 14th Edition [http://www3.weforum.org/docs/WEF\\_Global\\_Risks\\_Report\\_2019.pdf](http://www3.weforum.org/docs/WEF_Global_Risks_Report_2019.pdf))

The information in Fig. 1 was derived from a survey of WEF stakeholders (e.g., business leaders, senior politicians...), who were asked to select the three trends that they thought to be the most important in shaping global development in the next 10 years. For each of the three trends identified, respondents were asked to select the risks that are most strongly driven by those trends. The size of the features and thickness of connections illustrate weighting derived from the number of responses.

Interestingly, the spread of infectious diseases is considered as a societal risk and in this illustration is so small as to be almost invisible. In contrast to Table 1, it may be noted that familiar hazards such as road accidents, alcohol and drug abuse, or those predicted from increasing antimicrobial drug resistance, do not appear at all in the Figure. It should be emphasised that WEF is not unique in polling “experts” to identify critical attributes of complex systems and, indeed, this has been a standard approach adopted by think tanks and policy institutes since the early twentieth century. However, this simplistic approach seems much less applicable for conditions in the twenty-first century.

### Pandemics from a risk management perspective

The primary aim is to introduce a more formal, structured approach to risk management that can provide a better perspective on the causes and consequences of pandemics. To make best use of advanced Knowledge Management (KM) tools (as discussed further below), it is useful to begin with a formal ontology (e.g., Gruber, 1995) that defines the relationships between the factors directly causing a threat, the top-level drivers of these and major primary or secondary impacts. Review of a diverse range of literature results in Fig. 2, which aims to capture key factors and their relationships in a simple manner. To some extent, the choice of key factors reflects the perspectives of the team producing the ontology, but as this is extended to further levels of detail, it can be checked that these are comprehensive in terms of capturing the most important issues (many of which would presently be within the box “Increasing vulnerability to other hazards”—e.g., loss of

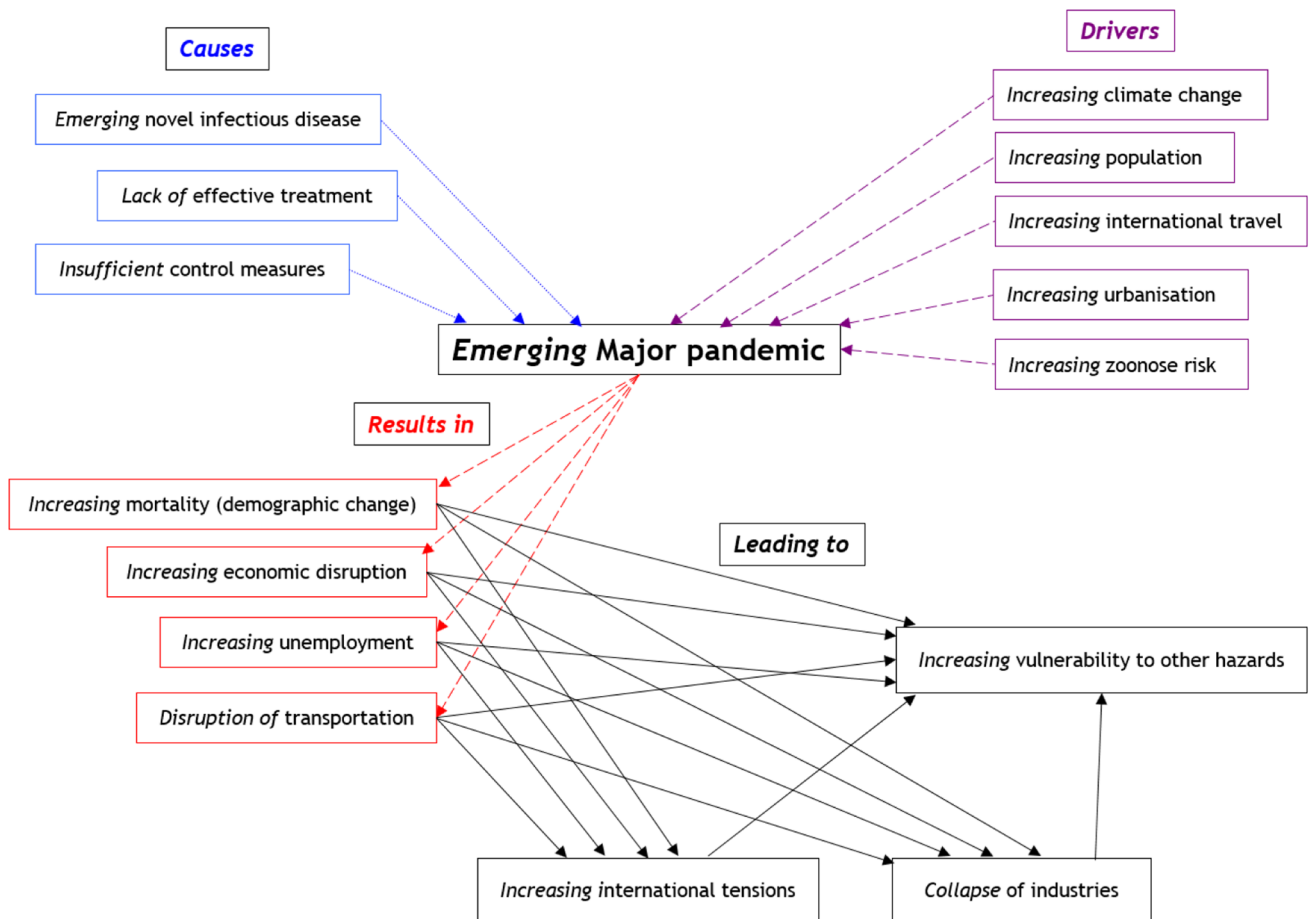


Fig. 2 Example of ontology defining the key global event “Major Pandemic” which is specified in terms of its status as “Emerging”

diversity, loss of educational infrastructure, increasing mental illness... as presently seen for COVID). The complete ontology can be subject to peer review to build confidence in both its structure and completeness.

Although the focus here is on pandemics, this approach is generally applicable to any global threat and, indeed, needs to be so, as major threats are often coupled together. Even though Fig. 2 provides only a top-level overview, it highlights coupling of pandemic risks to other developing threats (such as climate change and over-population) or trends (e.g. increasing international travel and urbanisation), thus emphasising the limited applicability of older historical analogues that represent very different boundary conditions. An additional benefit to establishing an ontology is that it ensures all terminology used is clearly defined, thereby facilitating the multi-disciplinary communication that is inevitably required.

On the basis of this ontology, capture of key knowledge can be facilitated by knowledge mining that takes advantage of the fact that most relevant information is now readily available in electronic form. As this knowledge encompasses a very wide range of disciplines within the physical, biological and social sciences, advanced KM tools can produce and structure the resultant knowledge base in a way that allows integration and synthesis to derive key messages, set in a context that includes ethical (including religious) and political boundary conditions (e.g., <http://www.knowledge-management-tools.net/>). Such tools also have the advantage of enhancing/facilitating the multi-disciplinary collaboration required for such a complex assessment of risks (Makino et al. 2011).

Although prediction of the future is inherently impossible—a fact that should receive more emphasis—a well-structured knowledge base allows credible scenarios of potential future evolution to be developed (NEA, 2001). Utilisation of a formal scenario development process allows these to be produced in a transparent manner—for example by describing the global environment in terms of relevant FEPs: Features (key system components), Events (distinct perturbations that can be localised in time) and Processes (the evolving interactions between features and events, which are often strongly

coupled with each other). Examples of these components and their classification are summarised in Table 2, developed as for Fig. 2 for the global event “Major Pandemic”.

Although scenarios can never be complete, the aim is that they should provide a wide enough range to bound the evolution that will be actually experienced. This range is produced by modifying the actual FEPs considered as significant for specific scenarios and the weighting assigned to them, in terms of potential impacts. The level of treatment of any resulting scenario depends on both its probability of occurrence (classed qualitatively, e.g. as *likely*, *less likely* and *very unlikely*) and consequences (e.g. *minor*, *major* or *catastrophic*). Although the focus is on likely scenarios with major impacts, any scenario with impacts tending towards catastrophic should be considered even if its likelihood were considered to be low (e.g. black swan event). A key problem here is the potential for a perturbation to reach a tipping point, where positive feedbacks can lead to runaway collapse of key infrastructure that greatly magnifies consequences (discussed further below in reference to Fig. 5).

This can be seen by considering the secondary impacts of a pandemic, as illustrated in Fig. 2. For example, huge impacts of COVID-19 on tourism have already been experienced—hitting an industry responsible for about 10% of global GDP and employment (e.g., <https://wtcc.org/Research/Economic-Impact>). This is particularly important in many vulnerable developing countries, especially when coupled with other factors such as decreased economic aid or demand for exports. Thus, the large second wave of COVID cases in the 2020 Northern Hemisphere winter is already starting to cause local/regional economic collapse, potentially then leading to migration of populations from most afflicted areas, increasing tensions and causing a greater risk of conflict.

Economic collapse, in turn, both increases risks of loss of control of the existing pandemic and further new diseases emerging and spreading, giving a positive feedback loop that will impact even the more developed economies. Although tipping points are often ignored in risk models with the justification that they are considered to be unlikely, in truth the complexity involved generally prevents any justifiable

**Table 2** Features, Events and Processes (FEPs) associated with global event “Major Pandemic” specified as “increasing”

Features	Events	Processes
Increasing population	Emerging novel infectious disease	Increasing direct illness/mortality
Increasing urbanisation	Local to national/international spread of the disease	Increasing indirect physical/mental health impacts
Continuing global temperature increase	Collapse of health care systems	Increasing economic disruption
Increasing international travel	Collapse of local/regional/national economies and infrastructure	Increasing disruption to transportation
Lack of effective treatment/control measures		Increasing unemployment
Public refusal to adhere to control measures		Increasing social unrest
		Increasing international tensions

estimate of probability. In cases where tipping points are credible but can be prevented by cost-effective measures, the precautionary principle could justify implementing these.

Although the goal is to analyse the consequences of representative scenarios quantitatively, a qualitative description of evolution with time may be sufficient to provide guidance for risk managers. In particular, illustration of all key FEPs and their interactions allows the constraints and uncertainties associated with existing models of environmental sub-components (e.g., regional infection propagation) to be appreciated. An open question is what level of complexity or detail is required for such scenarios; this can be somewhat subjective, but a general rule of thumb is that further detail should not be added if it does not significantly change the conclusions from resulting consequence analysis. As is seen from the following sections, scenarios include many coupled processes and adding superfluous detail risks losing the holistic overview that is a main goal.

## Practical application of the risk management toolkit

In terms of application of established tools, it is useful to consider two fundamental risk management goals—description of the current status together with its potential evolution with time and assessment of the pros and cons of different intervention strategies. The current status can be established by consideration of a form of “event tree” that traces the evolution of any pandemic, with a focus on geographic spread and the consequences in terms of mortality (direct and indirect) and economic impact—linked to the specific counter-measures that can be considered (Fig. 3).

The starting point is localised emergence of a novel disease with characteristics that could potentially lead to a pandemic—being highly infectious and having serious health impacts. If this can be identified quickly, local counter-measures can be implemented in a highly cost-effective manner (boxes coloured red in Fig. 3). Countermeasures would include: containment to prevent wider spread of the disease, focused medical care to reduce mortality or other serious health impacts, lockdown to reduce even local transmission and socio-economic support to reduce the impacts of such a lockdown. For example, in terms of indirect mortality (due to reduced availability of medical care) and other indirect consequences such as unemployment, mental stress, malnutrition, etc.

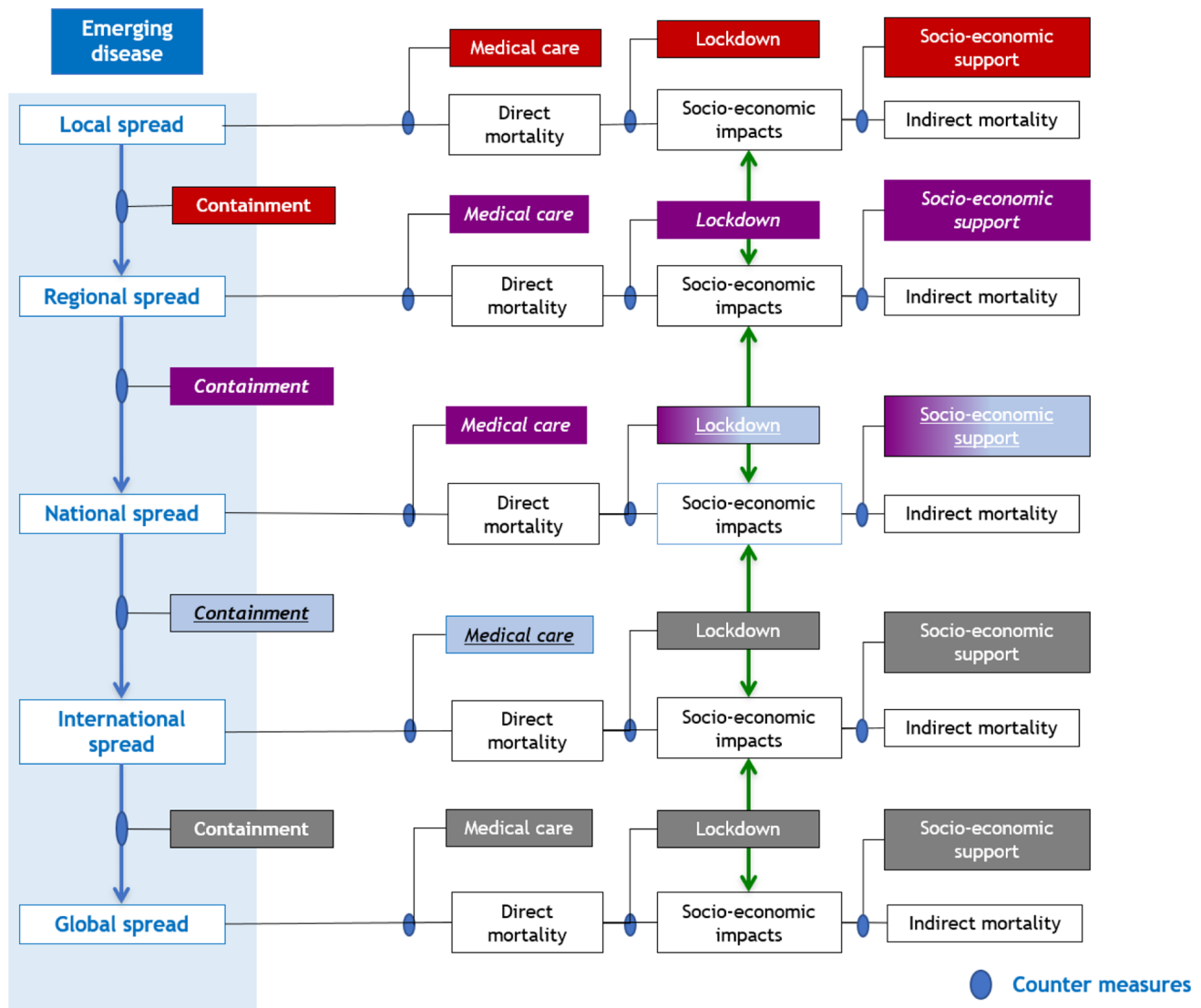
In the event of failure of local containment, the same counter-measures can be implemented on a regional scale, although the cost-effectiveness is inherently reduced (boxes coloured purple). The difficulties of containment increase and the cost/benefit of counter-measures decrease as the geographical area expands so that, for many large countries,

the practicality and value of particular counter-measures become very limited (blue colouring). Beyond the national scale, the movements of materials and people essential to the global economy are so complex that counter-measures at this level are generally ineffective (grey boxes).

To develop a holistic overview, a comprehensive description of the initial system, which identifies all relevant top-level FEPs and the interactions between them, is subject to specified perturbations initiated by a particular trigger. Although there are many ways to represent the global environment (e.g. Fig. 1), it is important that the primary focus is on identifying major constraints on evolution with time and key links between them. To provide more of an overview, the global system Processes associated with development of a generic pandemic Event can be identified, building on Fig. 2 and Table 2 (Fig. 4).

The arrows indicate the direction of impacts, full arrows being predominantly positive and dashed arrows are either mixed or predominantly negative. Double-headed arrows indicate complex feedbacks. Black arrows represent coupling that is effectively independent of emergence of a pandemic; red arrows are those representing direct impacts and blue ones important secondary impacts. Figures 2, 3 and 4 together thus illustrate the complexities of the system that numerical models try to capture and support the general statements on the problems involved in attempting this, noted in the introduction.

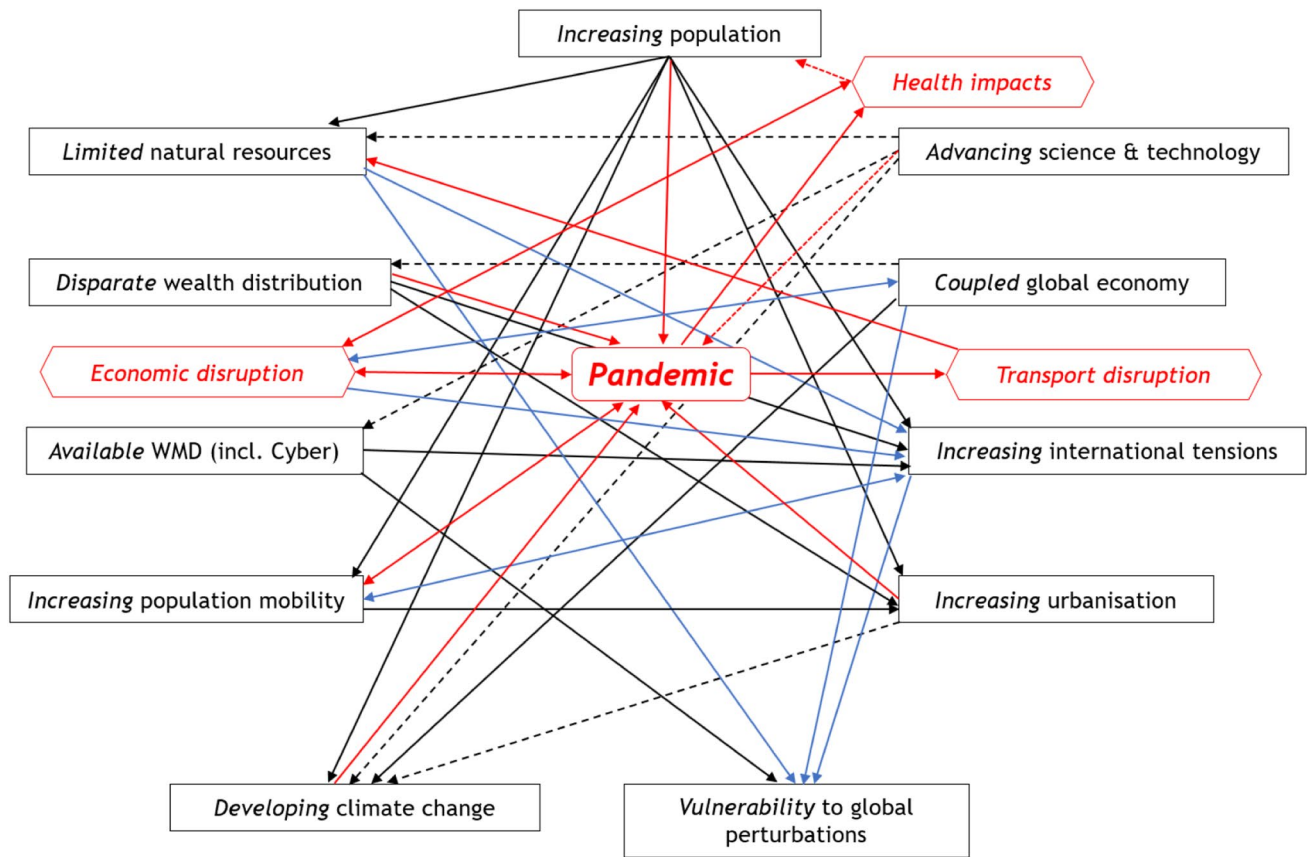
Key contributors to the probability of occurrence, such as increasing population, population mobility, urbanisation and climate change are all evolving with time and hence, this factor is inherently highly uncertain and will probably increase with time unless there are major system changes (e.g., fundamental advances in medical science). The approach taken in Fig. 4 can be developed further to indicate the impact of different pathogen characteristics such as associated disease, infectivity and mortality rates (Fig. 5). In particular, as the impacts in terms of rate of spread of the disease and its consequences in terms of mortality and strain placed on health services increase, there is the risk of hitting a tipping point, where positive feedbacks can lead to a “snowball effect” of collapse or failure of essential infrastructure and services, due to strong coupling between them. This is already being seen in a number of countries and regions as second (or even third) infection peaks of the COVID-19 pandemic hit, and secondary socio-economic impacts often cause greater concern than the primary health effects. For a more infective or aggressive infection, this could develop faster, before mitigating negative feedbacks (like vaccine development or changes in public behaviour) offer a potential brake to pandemic development. Of course, in the worst case, even extreme pandemics will burn out but this is only when the drivers for it are removed and negative feedback results from massive global impacts.



**Fig. 3** Event tree for a generic pandemic, tracing how it emerges and the impacts of counter-measures on different scales: see text for clarification

Such a holistic overview can also be used to evaluate responses. Despite the complexity of the overall system, the impacts of different response strategies can be assessed, albeit in a relative, qualitative manner by polling expert opinion and capturing it using simple illustrative approaches (e.g., “spiders’ web diagrams”), as shown in Fig. 6. The examples here are illustrative only, based on the assessment above and experience so far in the present pandemic, but can be developed further for any specific pandemic scenario. Here, the user-friendliness of the approach facilitates capture of input from a wider range of stakeholders—in particular policymakers—encouraging them to buy into the assessment in a way that is not possible with an approach based on complex numerical models.

The COVID-19 experience has shown that significant and prolonged lockdowns yield major disruptions to both national and world economies/transportation, leading to indirect health impacts that, especially in developing countries, may greatly exceed those directly due to the pandemic itself. For any pandemic of the same scale as COVID-19, even indirect mortality, whilst unlikely to reverse world population growth (which is estimated to increase from 7.7 billion in 2019 to 8.5 billion in 2030 (<https://population.un.org/wpp>)), could be much larger than the direct death tolls arising from the minimum intervention case. In addition, infrastructure disruptions will increase vulnerability to global perturbations (current



**Fig. 4** Overview of impacts of a pandemic on the coupled network of global threats and trends (WMD Weapons of mass destruction)

examples being impacts of locust swarms in India and extreme weather events around the world).

### Reducing the probability and/or impacts of future pandemics

In general terms, future global-scale hazards can be characterised as being either preventable or not, with assessment based on existing technology and without consideration of whether socio-political constraints could limit implementation of counter-measures. Based on current technology, future pandemics at least on a scale equivalent to COVID-19 cannot be precluded and hence measures should focus on reducing their probability and/or impacts (e.g., McCloskey et al. 2014). Such an approach is well established in the nuclear industry and involves implementation of concepts such as:

- **Fail-safe:** acknowledging that some systems will inevitably fail, but ensure that such failure will not degrade safety (e.g. modern reactor designs that will cool naturally even in the case of loss of all site power).

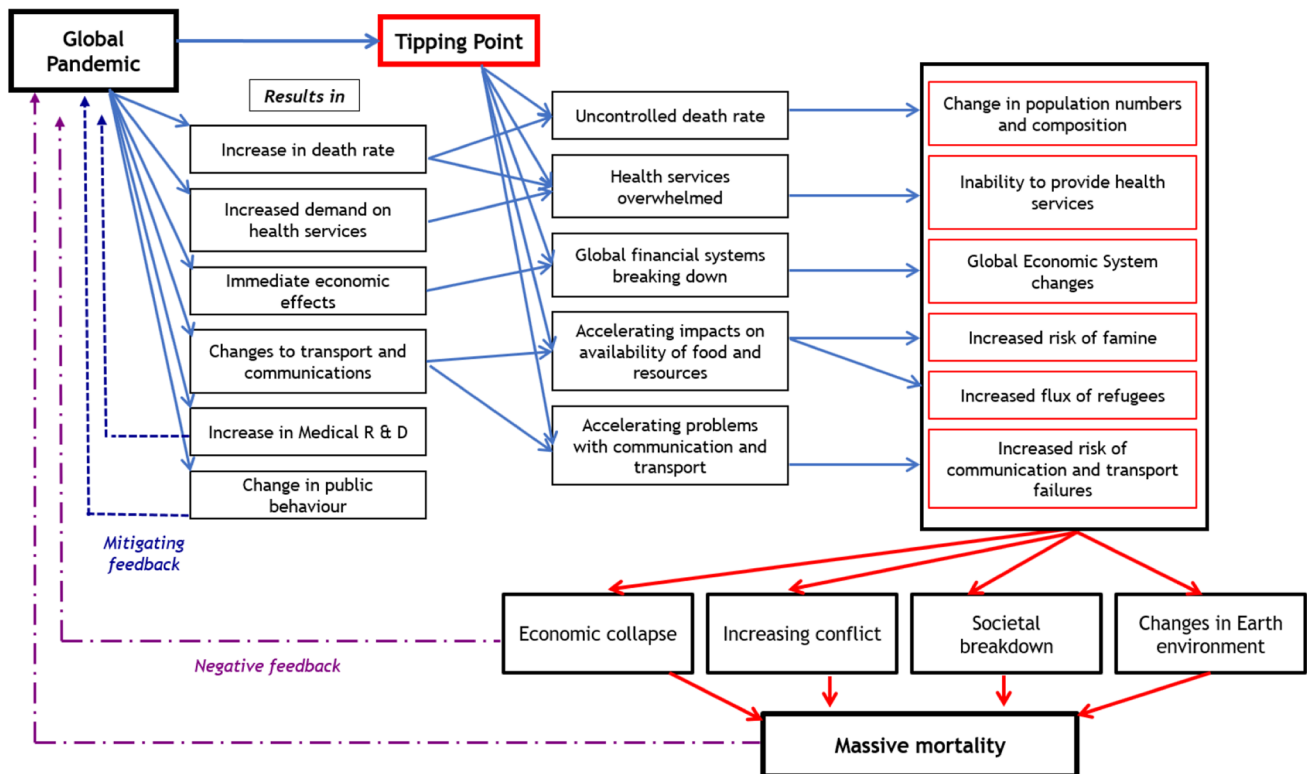
- **Robustness/defence in depth:** incorporation of safety barriers that are very simple (e.g. passive, not requiring any human interactions) and with multiple components that provide a sequence of redundant barriers.
- **Resilience/graceful failure:** even if systems fail, they do so in a controlled manner, which facilitates recovery and any required remedial action.

Taking these concepts over for pandemics requires a detailed assessment of the triggers involved and the coupling of all relevant features and processes, but the general principles can be illustrated.

For example, critical facilities and infrastructure should be designed (or retro-fitted) to be fail-safe to the extent possible, noting that scenarios may often include common-mode failure, resulting in simultaneous loss of other key services (e.g. electrical power distribution networks, transport networks to supply critical materials). As a specific example, wider geographic distribution of vaccine production facilities would reduce risks from disturbances of localised production centres or of transport networks.

Robustness and defence in depth could be incorporated into disaster response plans, which should also emphasise





**Fig. 5** Example of potential tipping points and associated feedbacks. The scale of the impact of a Global pandemic depends on the nature of the pathogen and associated disease, its infectivity and associated mortality rates

flexibility and incorporate measures to reduce volatility and irrationality in political and economic/market responses. While it is true that responses to even a major nuclear accident (e.g., Fukushima Daiichi) are much more spatially restricted than a global pandemic, the principals involved are certainly relevant at a regional and national level. For example, planning of military training and infrastructure could include their flexible use in case of events such as pandemics, allowing personnel to support civil services in key areas (medical, transportation, engineering) and providing purchasing focus on equipment that will support this (e.g. field hospitals, helicopters, mobile power supplies). Resilience can be incorporated by distribution of facilities/infrastructure so that, in the case of single failures, load can be spread over those remaining.

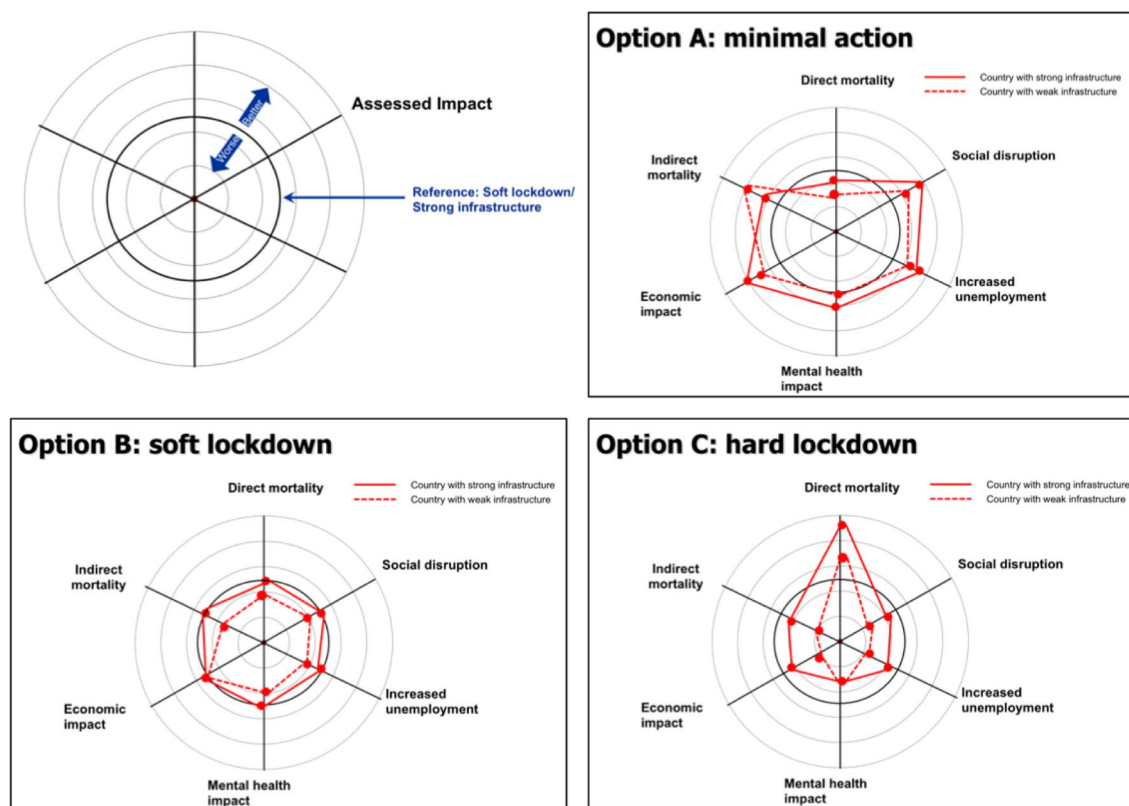
During development of risk management plans, a further lesson from the nuclear industry is the need for extreme caution when using numerical models. As noted above, the simplifications involved can be so great that output has huge associated uncertainties (if not completely wrong) and, even if broadly correct within an order of magnitude or so, can be misleading in the way results are presented. Rather than use of numerical models alone, more emphasis should be on scenario descriptions that capture FEPs in a qualitative or semi-quantitative manner, with special emphasis on

completeness in terms of processes and coupling between them. Inevitably, this will require solicitation of expert opinion, but this needs to be done in a structured manner to avoid the known problems of groupthink (e.g., using a Think Tank group approach—Umeki et al. 2011).

Finally, it is clear that, in democracies at least, implementation of risk counter-measures requires acceptance by all stakeholders. Despite the fact that the issues are complex, it is essential that public concerns are polled and taken into account to the extent possible. Here again, tools are available to determine stakeholder desires and incorporate these into complex projects such as carbon capture and storage (e.g., Mors (2013). A broader example of wider stakeholder involvement in developing radioactive waste disposal solutions can be seen in the Nuclear Energy Agency (NEA) Stakeholder Forum which has met regularly since 2001 ([https://www.oecd-nea.org/jcms/pl\\_26865/forum-on-stakeholder-confidence-fsc](https://www.oecd-nea.org/jcms/pl_26865/forum-on-stakeholder-confidence-fsc)).

## Conclusions and a look to the future

This paper is based on the observation that the pandemic threats faced in the twenty-first century have no good historical analogues and hence a novel methodology is



**Fig. 6** Comparison of impacts of different response levels for countries with different infrastructure

required to assess and respond to them appropriately. As has been recently demonstrated, this is now urgent as in terms of consequences, these have the potential to match or exceed major disasters of the twentieth century (e.g., the two world wars). Over the last few decades, the nuclear industry has already been required to evaluate novel threats over unique timescales and hence the approaches and tools developed could form a good starting point as discussed above. Applications of these approaches are illustrated for a range of different tasks associated with identifying the causes of pandemics, the factors influencing their impacts and the pros and cons of different mitigation approaches.

Knowledge management tools for risk assessment thus seem to provide a promising basis for planning pandemic risk reduction and managing responses. It should be emphasised, however, that risk management tools do not change the key role of decision makers, at best, they only provide a better basis for making decisions. It has also to be emphasised that the illustrations developed with these tools also need to be used with care, to avoid over-interpretation. These do not replace numerical models, but can help put them in context as part of the process of making the decision-making more transparent and facilitating dialogue so that input from a wider range of stakeholders can be obtained.

Due to limited resources, efforts here have been limited to a top, conceptual level analysis, although more detailed studies could be implemented quickly and cost-effectively as proven tools and experience using them become available. The need now is for further support—potentially as part of a collaboration with national or international risk management organisations. Especially as many of the concerns and recommended countermeasures to reduce risks are common to managing pandemics and other natural or anthropogenic risks, extending the assessment to include a wider perspective would be useful and assure that efforts are as cost-effective as possible.

**Acknowledgements** We thank the Editor and anonymous reviewers for their very positive and constructive comments which helped us improve and enhance the manuscript.

## References

- Allen RD, Hermanson DR, Kozloski TM, Ramsay RJ (2006) Auditor risk assessment: insights from academic literature. *Acc Horiz* 20(2):157–177. <https://doi.org/10.2308/acch.2006.20.2.157>
- Aven T (2015) Risk assessment and risk management: review of recent advances on their foundation. *Eur J Oper Res* 2:531–613. <https://doi.org/10.1016/j.ejor.2015.12.023>

- Baldwin R, Weder di Mauro B (2020) Introduction. In: Baldwin R, Weder di Mauro B (eds) *Economics in the time of COVID-19*. Centre for economic policy research press, Washington, pp 1–30 (ISBN: 978-1-912179-28-2)
- Bedford J, Enria D, Giesecke DL, Ihekweazu C, Kobinger LaneMemishOhSallSchuchatUngchusakWieler GLHCZMDAAAKLH (2020) COVID-19: towards controlling a pandemic. *Lancet* 395(1022):1015–1018. [https://doi.org/10.1016/S0140-6736\(20\)30673-5](https://doi.org/10.1016/S0140-6736(20)30673-5)
- Bloom DE, Cadarette D (2019) Infectious disease threats in the twenty-first century: strengthening the global response. *Front Immunol*. <https://doi.org/10.3389/fimmu.2019.00549>
- Boccaletti S, Ditto W, Mindlin G, Atangana A (2020) Modeling and forecasting of epidemic spreading: The case of Covid-19 and beyond. *Chaos, solitons and fractals* 135, p.109794. <https://doi.org/10.1016/j.chaos.2020.109794>
- Cheng VCC, Lau SKP, Woo PCY, Yuen KY (2007) Severe acute respiratory syndrome coronavirus as an agent of emerging and re-emerging infection. *Clin Microbiol Rev* 20:660–694
- Eling M, Schnell W (2016) What do we know about cyber risk and cyber risk insurance? *J Risk Financ* 17(5):474–491. <https://doi.org/10.1108/JRF-09-2016-0122>
- Fakhrudin BSHM, Blanchard K, Ragupathy D (2020) Are we there yet? The transition from response to recovery for the COVID-19 pandemic. *Prog Disaster Sci* 7:100102
- Fan Y, Jamison DT, Summers LH (2018) Pandemic risk: how large are the expected losses? *Bull World Health Organ* 96(2):129–134. <https://doi.org/10.2471/BLT.17.199588>
- Ferguson NM, Cummings DAT, Fraser C, Cajka JC, Cooley RC, Burke DS (2006) Strategies for mitigating an influenza pandemic. *Nature* 442:448–452. <https://doi.org/10.1038/nature04795>
- Flage R, Aven T (2015) Emerging risk—conceptual definition and a relation to black swan type of events. *Reliab Eng Syst Saf* 144:61–67. <https://doi.org/10.1016/j.res.2015.07.008>
- Gossling S, Scott D, Hall CM (2020) Pandemics, tourism and global change: a rapid assessment of COVID-19. *J Sustain Tour* 29(1):1–20. <https://doi.org/10.1080/09669582.2020.1758708>
- Gruber T (1995) Toward principles for the design of ontologies used for knowledge sharing. *Int J Hum-Comput Stud* 43(5–6):907–928
- Keogh-Brown MR, Smith RD, Edmunds JW, Beutels P (2010) The macroeconomic impact of pandemic influenza: estimates from models of the United Kingdom, France, Belgium and The Netherlands. *Eur J Health Econ* 11(6):543–554. <https://doi.org/10.1007/s10198-009-0210-1>
- Makino H, Umeki H, Hioki K, McKinley IG (2009) The Challenge of Development of a Holistic Waste Management Approach to Support the Nuclear Renaissance. *Waste Management Symposium, (2009) Waste Management for the Nuclear Renaissance, Proceedings 1–5 March 2009, Arizona, Phoenix*
- Makino H, Hioki K, Umeki H, Takase H, McKinley IG (2011) Knowledge management for radioactive waste disposal: moving from theory to practice. *Int J Nucl Knowl Manag* 5:93–110
- McCloskey B, Dar O, Zumla A, Heymann DL (2014) Emerging infectious diseases and pandemic potential: status quo and reducing risk of global spread. *Lancet* 14(10):1001–1010. [https://doi.org/10.1016/S1473-3099\(14\)70846-1](https://doi.org/10.1016/S1473-3099(14)70846-1)
- McDermott TKJ, Surminski S (2018) How normative interpretations of climate risk assessment affect local decision-making: an exploratory study at the city scale in Cork, Ireland. *Philos Trans R Soc Math Phys Eng Sci* 376:20170300
- McKinley IG, McCombie C, Zuidema P (1997) Assessing and presenting risks from deep disposal of high-level radioactive waste, advances in safety and reliability, (Proc. ESREL'97, Lisbon Portugal C. Guedes Soares, ed), 1, 577–582, Pergamon
- Mors ET et al (2013) A comparison of techniques used to collect informed public opinions about CCS; opinion quality after focus groups discussions versus information choice questionnaires. *Int J Greenh Gas Control* 18:256–263
- NEA (2001) Scenario development methods and practice. OECD Nuclear Energy Agency publication. [https://www.oecd-ilibrary.org/nuclear-energy/scenario-development-methods-and-practice\\_9789264193536-en](https://www.oecd-ilibrary.org/nuclear-energy/scenario-development-methods-and-practice_9789264193536-en). Accessed Oct 2020
- Oehmen J, Locatelli G, Wieda M, Willumsen P (2020) Risk, uncertainty, ignorance and myopia: their managerial implications for B2B firms. *Ind Mark Manag* 88:330–338
- Oliver D, Daly F, Martin FC, McMurdo MET (2004) Risk factors and risk assessment tools for falls in hospital in-patients: a systematic review. *Age Ageing* 33(2):122–130. <https://doi.org/10.1093/ageing/afh017>
- Rubio JL, Bochet E (1998) Desertification indicators as diagnosis criteria for desertification risk assessment in Europe. *J Arid Environ* 39(2):113–120. <https://doi.org/10.1006/jare.1998.0402>
- Sodhi MS, Son B-G, Tang CS (2012) Researcher's perspectives on supply chain risk management. *Prod Oper Manag* 21(1):1–13. <https://doi.org/10.1111/j.1937-5956.2011.01251.x>
- Trump BD, Linkov I (2020) Risk and resilience in the time of the COVID-19 crisis. *Environ Syst Decis* 40:171–173
- Umeki H, Takase H, McKinley IG (2011) Geological disposal: KM challenges and solutions. *Knowl Manag Res Pract* 9:236–244
- Wang N, Fu Y, Zhang H, Shi H (2020) An evaluation of mathematical models for the outbreak of COVID-19. *Precis Clin Med* 3(2):85–93. <https://doi.org/10.1093/pcmedi/pbaa016>
- WEF World Economic Forum. (2019) The Global Risks Report 2019, 14th Edition, [http://www3.weforum.org/docs/WEF\\_Global\\_Risks\\_Report\\_2019.pdf](http://www3.weforum.org/docs/WEF_Global_Risks_Report_2019.pdf). Accessed Oct 2020
- Yarovaya L, Brzeszczyński J, Goodell JW, Lucey BM, Lau CK (2020) Rethinking financial contagion: information transmission mechanism during the COVID-19 pandemic. SSRN. <https://doi.org/10.2139/ssrn.3602973>

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.