Futures xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Futures

journal homepage: www.elsevier.com/locate/futures

Classifying global catastrophic risks

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ARTICLE INFO

Keywords:
Global catastrophic risk
Existential risk
Foresight
Planetary boundaries
Anthropogenic risk
Classification
Interdisciplinary
Risk assessment
Prevention and mitigation

ABSTRACT

We present a novel classification framework for severe global catastrophic risk scenarios. Extending beyond existing work that identifies individual risk scenarios, we propose analysing global catastrophic risks along three dimensions: the critical systems affected, global spread mechanisms, and prevention and mitigation failures. The classification highlights areas of convergence between risk scenarios, which supports prioritisation of particular research and of policy interventions. It also points to potential knowledge gaps regarding catastrophic risks, and provides an interdisciplinary structure for mapping and tracking the multitude of factors that could contribute to global catastrophic risks.

1. Introduction

In our uncertain times it is good to have something we can all agree on: global catastrophes are undesirable. As our science advances we gain a better understanding of a broad class of global catastrophic risk (GCR) scenarios that could, in severe cases, take the lives of a significant portion of the human population, and may leave survivors at enhanced risk by undermining global resilience systems (Baum & Tonn, 2015; Bostrom, 2002; Bostrom & Ćirković, 2008; Posner, 2004; Rees, 2003; Tonn & MacGregor, 2009). Much progress has been made in identifying individual GCR scenarios, and in compiling lists of the scenarios of greatest concern, but there is currently no known methodology for compiling a comprehensive, interdisciplinary view of severe global catastrophic risks. While a fully complete list of GCRs may remain beyond reach, we present here a classification framework designed specifically to draw on as broad a knowledge base as possible, to highlight commonalities between risk scenarios and identify gaps in our collective knowledge regarding global catastrophic risks.

To date, research on global catastrophic risk scenarios has focused mainly on tracing a causal pathway from a catastrophic event to global catastrophic loss of life (Asimov, 1981; Bostrom & Ćirković, 2008; Coburn et al., 2014; Cotton-Barratt, Farquhar, Halstead, Schubert, & Snyder-Beattie, 2016; Turchin, 2015). Such research has been fruitful in identifying and assessing a range of such GCR scenarios. Some severe GCR scenarios have posed a persistent threat to humanity since our emergence as *Homo sapiens* (e.g. impact by a 10 km astronomical object, or a volcanic super-eruption of 1000 km^3 of tephra). Other scenarios have increased in likelihood following human population expansion and the accompanying increase in resource demands (e.g. natural pandemics or ecosystem collapse). In addition, novel GCR scenarios can accompany new technologies: some of these are relatively well established (e.g. "nuclear winter" or an engineered pandemic); others are more speculative (e.g. accidents in or weaponisation of advanced artificial intelligence, or environmental shocks from ill-judged geoengineering efforts aimed at mitigating climate change).

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https://doi.org/10.1016/j.futures.2018.02.001
Received 26 May 2017; Received in revised form 26 January 2018; Accepted 12 February 2018

Please cite this article as: Avin, S., Futures (2018), https://doi.org/10.1016/j.futures.2018.02.001

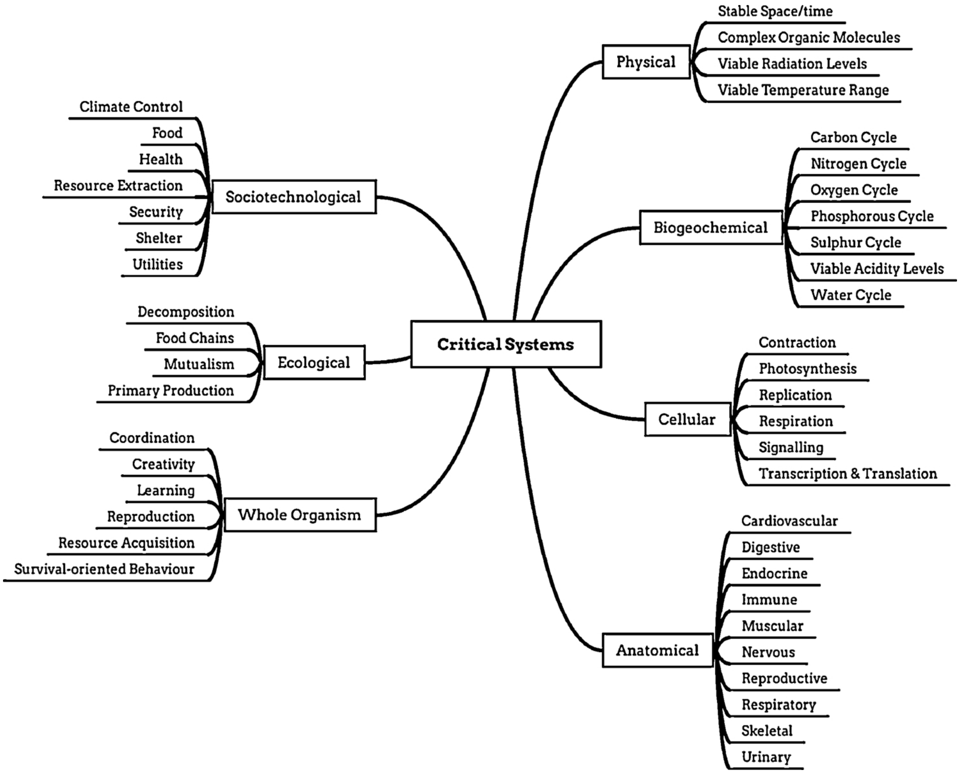


Fig. 1. Classification of Critical Systems aimed at identifying Global Catastrophic Risk scenarios. Systems are grouped at different levels, arranged from "lower level" to "higher level" in a clockwise fashion starting with the "Physical" group on the top-right.

However, compiling a comprehensive list of plausible GCR scenarios requires exploring the interplay between many interacting critical systems and threats, beyond the narrow study of individual scenarios that are typically addressed by single disciplines. The classification framework presented here breaks down the analysis of GCR scenarios into three key components: (i) a critical system (or systems) whose safety boundaries are breached by a potential threat, (ii) the mechanisms by which this threat might spread globally and affect the majority of the human population, and (iii) the manner in which we might fail to prevent or mitigate both (i) and (ii). For example, a major astronomical impact may lead to a global catastrophe if we lack the technology to deflect it (mitigation failure), *and* it raises a cloud of dust that spreads around the world (global spread mechanism), *and* that cloud of dust blocks sunlight for a sufficient length of time to undermine the global food system in a manner that we cannot overcome (critical system affected). Other scenarios will have different combinations of one or more mitigation failures, one or more global spread mechanisms, and one or more critical system breaches.

In order to gain a holistic picture of potential global catastrophes, knowledge about each of the three system components needs to be explored and shared. By first constructing a classification from the broad range of known critical systems, global spread mechanisms, and prevention and mitigation failures, and then by classifying known GCR scenarios according to these dimensions, we aim to: (i) showcase the GCR relevance of a variety of scientific disciplines, (ii) highlight how commonalities between threat scenarios have research and policy implications, and (iii) highlight areas where there are potential gaps in our knowledge of global catastrophic risks. We also propose concrete steps for coordinating the broad-based, interdisciplinary research required to meet the challenges highlighted by the framework.

2. Critical systems

We define a "critical system" as any system or process that, if disturbed beyond a certain limit or scale, could trigger a significant reduction in humanity's ability to survive in its current form (see Fig. 1).

Building on the "life support systems" outlined in the research on so-called planetary boundaries (Rockström et al., 2009; Steffen et al., 2015) (many of which appear in our *biogeochemical* group), and their potential links to GCRs (Baum & Handoh, 2014), we identify critical systems and processes that, if disrupted, would affect human ability to survive. While we aim for comprehensiveness and minimal overlap, we acknowledge that different systems overlap. For example, while the processes affecting *ocean acidity* have direct effects on ecosystem stability and thus human life, there is significant overlap (causally, structurally and academically) with the global *water cycle*, *carbon cycle* and *sulphur cycle* systems.

In our classification framework, critical systems are grouped at different levels in a hierarchy, such that "higher-level" systems rely on the functioning of those at a "lower-level". Thus, the framework builds up from the stability of life-supporting *physical*

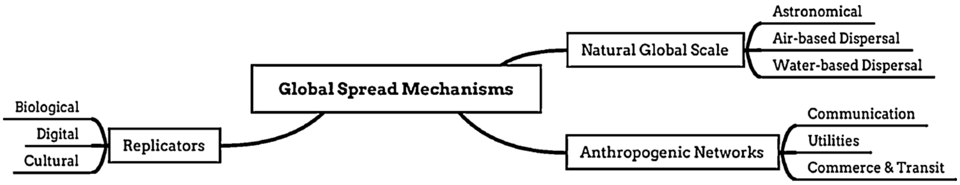


Fig. 2. Classification of Global Spread Mechanisms relevant to Global Catastrophic Risk.

systems, through *cellular* and other systems, right up to species-wide *ecological* and *sociotechnological* systems. "Lower-level" systems are directly linked to human survival (which relies on functioning *anatomical* systems, which in turn relies on *cellular* systems, etc.). "Higher-level" systems, especially technology-enabled ones such as the *food* and *health* systems, help maintain the human population at its current size, and provide resilience. If these "higher-level" systems were to be disturbed significantly in some scenario, e.g. through a severe and prolonged disruption to utilities networks (such as water and electricity), or through shock effects (such as social unrest), these could cause more harm than the system disturbance itself.

Identification of critical systems, and their cross-links, could also come from historical and archaeological study of more limited instances of human population collapse. For instance, the collapse of the Easter Island civilisation shows how excessive *resource extraction* (of palms for the making of canoes) led to ecological degradation, undermining *primary production* and *food chains*, which in turn led to failure of the Easter Island society's *food* system (Morrison, 2006). Further study of each critical system requires specialised expertise, often in more than one domain, as there is no one-to-one mapping from scientific disciplines to critical systems. Future work, conducted with collaboration with the wider scientific community, could lead to the demarcation of safe operating bounds for each critical system, following the example of Rockström et al. (2009).

3. Global spread mechanisms

For many critical systems, a failure of some instances of the system, e.g., regional crop failure, would fall far short of posing a GCR. In severe GCR scenarios, the failure of critical systems is coupled with some mechanism by which this failure spreads globally, thus potentially threatening the majority of the human population. In the framework, we separate the analysis of global spread mechanisms from the analysis of critical systems (Fig. 2). This separate focus on global spread allows us to identify relevant mechanisms (and means to manage or control them) as targets of study meriting further attention, and highlights interesting commonalities.

A critical system failure can spread globally without human intervention: some *astronomical* objects or events are sufficiently massive to have direct global effect, while other threats can spread through the dynamic systems of the *natural* environment, such as the *air*- and *water-based dispersal* systems. Dust and toxins could be spread naturally even if they do not replicate, though of course a self-replicating threat (e.g. a virus that affects multiple species of fish) could couple with a dynamic system (e.g. ocean currents) to achieve much faster spread.

In addition to natural spread, many risk scenarios, and especially emergent risk scenarios, rely on the highly connected nature of our species, both materially and conceptually. A modern pandemic can spread through airports and other mass-transit hubs of the globe-encompassing *transit* network, thus coupling a *biological replicator* (this might be, e.g., a bacterium itself, *or* a biological vector, e.g. a mosquito) to a highly connected *anthropogenic network*. A cyber attack can cascade through global critical systems at the speed of *digital communication,* shutting down *health* and *security* systems, and undermining *resource extraction* and *utilities* by disrupting mines and power plants (a *digital replicator*, such as a computer worm, could speed up the spread rate and reach).

Access to information can play a more abstract, but no less important, role in the spread of critical system failure. The widespread, and growing, access of individuals and groups across the globe to ideas, schematics, and manufacturing capabilities (e.g. Do-It-Yourself, or DIY, biology) through *digital* and *cultural* exchanges (e.g. online fora), enables novel hypothetical GCR scenarios. Such a scenario could start with, say, the accidental or malicious release of a home-grown pathogen, or the one-sided deployment of geoengineering efforts in an attempt to mitigate climate change. Some ideas encourage their own spread, e.g. schematics for communication devices, or ideas that encourage further sharing of those ideas (e.g. ideologies or viral videos), coupling *cultural replicators* with human interaction networks.

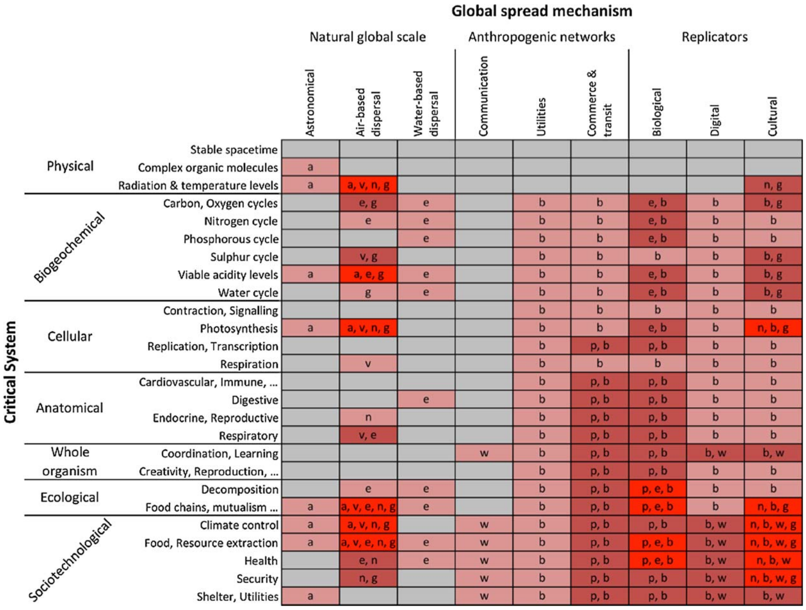
Table 1 illustrates how analysis of critical systems and analysis of global spread mechanisms might be combined into a single classification framework. The table presents a mapping from eight hypothetical GCR scenarios to the critical systems that are most likely to be undermined in each scenario, for each type of global spread mechanism. We have chosen a selection of severe GCR scenarios that are (i) familiar, (ii) considered plausible, and (iii) cover both natural and anthropogenic threats. This is far from a comprehensive list of scenarios, as the very framework presented here aims to help explore possible scenarios.

4. Prevention and mitigation failures

Analysing GCR scenarios along the dimensions of critical systems and spread mechanisms draws significantly on our understanding of the natural world and technical systems, and complements existing endeavours to classify risks of a smaller scale (IRDR, 2014). Holistic risk management, however, must take into account the human elements that moderate GCR through prevention and mitigation efforts, and how these efforts might fail. The challenge of preventing global catastrophes thus requires integration of the

Table 1

Classification of hypothetical global catastrophic risk scenarios by global spread mechanisms and critical systems affected. Letters represent eight examples of risk scenarios: asteroid impact (a), volcanic super-eruption (v), pandemic (natural) (p), ecosystem collapse (e), nuclear war (n), bioengineered pathogen (b), weaponised artificial intelligence (w), geoengineering termination shock (g). Cell colour represents number of catastrophic scenarios potentially compromising the critical system globally via the spread mechanism (grey: no likely disruption, light pink: one scenario, dark pink: two scenarios, red: three or more scenarios). Critical systems with an identical vulnerability profile to these risk scenarios have been omitted for brevity, indicated by ellipses (see Fig. 1 for the full list of systems). (For interpretation of the references to colour in this table legend, the reader is referred to the web version of this article.)



		Global spread mechanism								
		Natural global scale			Anthropogenic networks			Replicators		
Critical System		Astronomical	Air-based dispersal	Water-based dispersal	Communication	Utilities	Commerce & transit	Biological	Digital	Cultural
Physical	Stable spacetime									
	Complex organic molecules	a								
	Radiation & temperature levels	a	a, v, n, g							n, g
Biogeochemical	Carbon, Oxygen cycles		e, g	e		b	b	e, b	b	b, g
	Nitrogen cycle		e	e		b	b	e, b	b	b
	Phosphorous cycle			e		b	b	e, b	b	b
	Sulphur cycle		v, g			b	b	b	b	b, g
	Viable acidity levels	a	a, e, g	e		b	b	e, b	b	b, g
	Water cycle		g	e		b	b	e, b	b	b, g
Cellular	Contraction, Signalling					b	b	b	b	b
	Photosynthesis	a	a, v, n, g			b	b	e, b	b	n, b, g
	Replication, Transcription					b	p, b	p, b	b	b
	Respiration		v			b	b	b	b	b
Anatomical	Cardiovascular, Immune, ...					b	p, b	p, b	b	b
	Digestive			e		b	p, b	p, b	b	b
	Endocrine, Reproductive		n			b	p, b	p, b	b	b
	Respiratory		v, e			b	p, b	p, b	b	b
Whole organism	Coordination, Learning				w	b	p, b	p, b	b, w	b, w
	Creativity, Reproduction, ...					b	p, b	p, b	b	b
Ecological	Decomposition		e	e		b	p, b	p, e, b	b	b
	Food chains, mutualism ...	a	a, v, e, n, g	e		b	p, b	p, e, b	b	n, b, g
Sociotechnological	Climate control	a	a, v, n, g		w	b	p, b	p, b	b, w	n, b, w, g
	Food, Resource extraction	a	a, v, e, n, g	e	w	b	p, b	p, e, b	b, w	n, b, w, g
	Health		e, n	e	w	b	p, b	p, e, b	b, w	n, b, w
	Security		n, g		w	b	p, b	p, b	b, w	n, b, w, g
	Shelter, Utilities	a			w	b	p, b	p, b	b, w	b, w

work and expertise in and between the natural and the social sciences, on a global scale.

A particularly comprehensive existing risk management framework with such integrative characteristics and international scope is the Sendai Framework for Disaster Risk Reduction (SFDRR), adopted by 187 UN member states in 2015 (UNISDR, 2015). Although developed for natural rather than technological disasters, it considers many of the potential human factors that influence resilience and vulnerability to an unfolding disaster. We take a similar approach here, and identify potentially fragile areas in the global risk prevention and mitigation system (Fig. 3). Rather than aiming for comprehensiveness or exclusivity, it highlights that understanding these interdependent and complex human factors requires input from a wide range of disciplines beyond the natural sciences.

For instance, short-term thinking and a limited focus constitute *cognitive biases* affecting *risk perception* and *management* on the

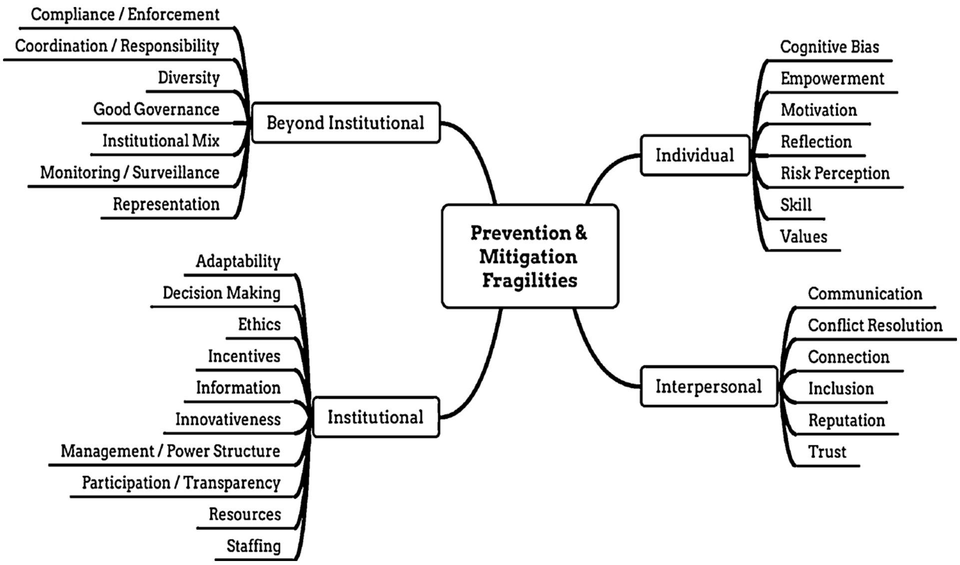


Fig. 3. Levels and dimensions of prevention and mitigation factors moderating global catastrophic risks.

individual and institutional level (as studied in psychology and behavioural economics); *unresolved political conflicts* and competing *ethical* notions of justice undermine international *cooperation* and burden-sharing on the institutional and supra-institutional level (as studied in e.g. law, philosophy and political science).

Some risks (e.g. natural pandemics) are already the focus of well-developed institutional systems (e.g. the World Health Organization), robust research activity and technical know-how. For GCRs from emerging technologies, however, the *institutional mix* and a research agenda are only just becoming established. Conventional disaster response (e.g. recovery and compensation), and even newer, comprehensive strategies (e.g. the "build back better" principle adopted in some countries post-disaster) are inadequate for addressing threat scenarios where there is limited reaction time and no second chance. For these cases, we need a novel framework that is at least as interdisciplinary as the SFDRR, but moves away from uni-dimensional, natural hazards and instead addresses complex, anthropogenic risks, which are far more likely to cause a severe global catastrophe (Rees, 2003). In particular, we have to focus on the prevention and mitigation of multidimensional risk scenarios that involve cascades of socio-technological, natural-technological ("natech") and technological-natural disasters.

As we confront emergent technological GCR scenarios, lessons can be learnt from previous smaller disasters. An instructive recent case of a multi-dimensional disaster scenario, albeit of local scope, is the Fukushima Dai'ichi nuclear accident, which laid bare failures at the interface of natural, scientific, technological, socioeconomic, legal and political realms. One such failure was the supervision of Japan's nuclear industry by the very same authorities that were to promote nuclear technology. Such an institutional setup, aggravated by *cognitive biases* (e.g. groupthink) in a sector with revolving doors to the regulator, was lacking adequate *incentive* structures, and was destined to result in conflicts of interest and regulatory capture. The international science and policy community therefore has the opportunity and the responsibility to co-create better risk prevention and mitigation systems, by engaging with researchers in the social sciences and humanities.

In principle it is possible to create a table that would expand on Table 1 to include the third dimension described here, i.e., prevention and mitigation failures. Such a table is, however, difficult to produce in practice, as the scenarios it helps us distinguish between are more fine-grained than those classified in Table 1. They are subcategories of these scenarios. For example, in Table 1 we classified "natural pandemic" as a single scenario, yet from a disaster policy and risk reduction perspective there is a clear difference between a pandemic that emerged due to underinvestment in veterinary surveillance, and a pandemic that emerged due to accidental release from a research laboratory. These scenarios can be further subdivided through the precise failures that allow the pandemic risk to materialise. If we consider just the accidental release scenario, we would start from the grid items occupied by 'p' in Table 1, which highlight intersections of the critical systems undermined by pandemic, such as anatomical systems, and the spread mechanisms for pandemic, which naturally include biological replicators but are also affected by anthropogenic networks as well as air- and water-based dispersal. To these we would add a third dimension, that would highlight all the prevention and mitigation failures potentially involved in accidental release, from failures of individual *skill* or *risk perception*, through institutional failures including malformed *incentives*, or insufficient *staffing* and *resources*, to supra-institutional failures of insufficient *monitoring* and *enforcement*.

5. Intended use of the classification system

In this section, we illustrate three key ways the classification system could potentially be used, although more may be discovered as the system is expanded and updated.

The first potential use is to prioritise risk reduction efforts. As can be seen in Table 1, scenarios with significantly different primary causes could manifest their GCR potential through a similar mechanism. For example, asteroid impact-, volcanic super-eruption-, and nuclear war scenarios all feature a risk of significant reduction of inbound solar radiation, disrupting food security and potentially leading to mass starvation. Not only does this draw attention to systems that are vulnerable to multiple hazards, but it also suggests there is value in considering these scenarios together in research and policy contexts, rather than thinking about them in isolation. For example, if accounting for volcanic super-eruptions, asteroid impacts and nuclear wars together, one might seriously consider risk management strategies that are robust to all scenarios, such as alternative food production systems to withstand the multi-year "winter" that might follow (Denkenberger & Pearce, 2015). While this does not preclude investment in nuclear disarmament or asteroid deflection, it demonstrates that alternative food policies may warrant more attention than first thought.

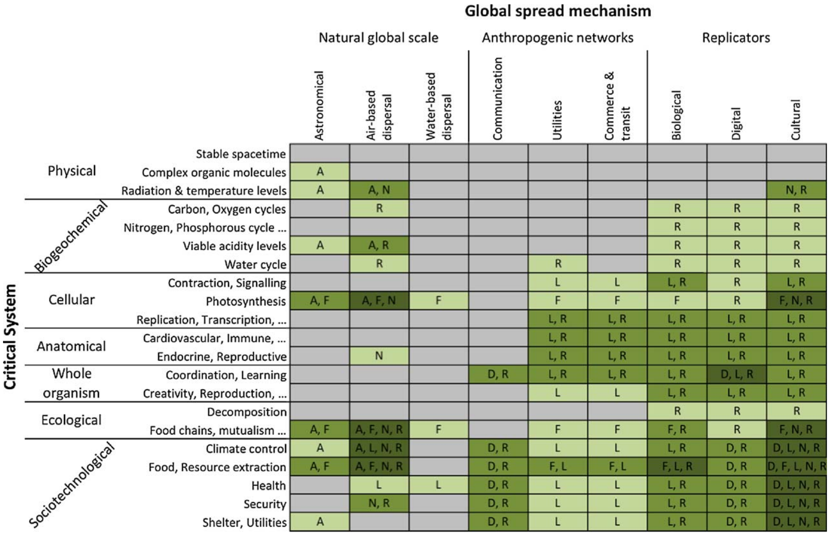
In addition to the challenge of securing food under reduced solar radiation, the classification framework highlights other areas that warrant further attention as potentially occurring from a range of threats. These include: how to manage the proliferation of potentially dangerous technologies, how we would function if human contact was restricted during a pandemic spread, and how we might make critical digital systems resilient to disruption by error or malice. The value of the classification system in highlighting potentially compatible risk reduction strategies is visualised in Table 2.

While expansion of this table into the third dimension of prevention and mitigation failures is beyond the scope of the current paper, we foresee that the creation of such an expansion, in a dynamic and collaborative fashion as described below, will have the same benefits as Tables 1 and 2. That is, it could be used to focus attention on prevention and mitigation failure categories that affect a range of GCR scenarios (e.g. better risk communication tools). While policy relevance to multiple risks does not directly entail higher priority for an intervention (as matters of probability, effectiveness and cost need to be taken into account), it could indicate the value of a comprehensive cross-risk analysis, to paint a more complete picture of the value of a proposed intervention.

The second potential use for the classification system lies in creating a live reference list of expertise for different risk scenarios. Our attempt to carve out categories in each dimension based on different academic domains should provide a quick index of the academic disciplines that are essential to "have at the table" when researching a specific risk scenario. Such an index could prove useful for policy makers who take responsibility for certain risk domains, or when an emerging risk is unfolding and an

Table 2

Classification of risk reduction strategies by global spread mechanisms and critical systems affected. Letters represent six examples of risk reduction strategies: asteroid deflection (A), digital resilience (D), food production through non-photosynthetic processes (F), limiting human contact during a pandemic (L), nuclear disarmament (N), restrictions on the diffusion of risky technologies (R). Cell colour represents number of risk reduction strategies addressing possible critical system failure and its global spread via the mechanism (grey: not addressed, light green: one strategy, green: two strategies, dark green: three or more strategies). Critical systems with an identical benefit profile from these strategies have been omitted for brevity, indicated by ellipses (see Fig. 1 for the full list of systems). (For interpretation of the references to colour in this table legend, the reader is referred to the web version of this article.)



		Global spread mechanism								
		Natural global scale			Anthropogenic networks			Replicators		
Critical System		Astronomical	Air-based dispersal	Water-based dispersal	Communication	Utilities	Commerce & transit	Biological	Digital	Cultural
Physical	Stable spacetime									
	Complex organic molecules	A								
	Radiation & temperature levels	A	A, N							N, R
Biogeochemical	Carbon, Oxygen cycles		R					R	R	R
	Nitrogen, Phosphorous cycle ...							R	R	R
	Viable acidity levels	A	A, R					R	R	R
	Water cycle		R			R		R	R	R
Cellular	Contraction, Signalling					L	L	L, R	R	L, R
	Photosynthesis	A, F	A, F, N	F		F	F	F	R	F, N, R
	Replication, Transcription, ...					L, R	L, R	L, R	L, R	L, R
Anatomical	Cardiovascular, Immune, ...					L, R	L, R	L, R	L, R	L, R
	Endocrine, Reproductive		N			L, R	L, R	L, R	L, R	L, R
Whole organism	Coordination, Learning				D, R	L, R	L, R	L, R	D, L, R	L, R
	Creativity, Reproduction, ...					L	L	L, R	L, R	L, R
Ecological	Decomposition							R	R	R
	Food chains, mutualism ...	A, F	A, F, N, R	F		F	F	F, R	R	F, N, R
Sociotechnological	Climate control	A	A, L, N, R		D, R	L	L	L, R	D, R	D, L, N, R
	Food, Resource extraction	A, F	A, F, N, R		D, R	F, L	F, L	F, L, R	D, R	D, F, L, N, R
	Health		L	L	D, R	L	L	L, R	D, R	D, L, N, R
	Security		N, R		D, R	L	L	L, R	D, R	D, L, N, R
	Shelter, Utilities	A			D, R	L	L	L, R	D, R	D, L, N, R

interdisciplinary team needs to be assembled in a hurry. This potential use underscores the importance of including the third dimension, which points to relevant academic disaster management expertise outside the natural sciences.

The third potential use for the system is as a tool to highlight highly uncertain or neglected corners of the GCR possibility space, and guide research efforts towards these corners, in the hope of discovering unknown unknowns. The combinatorial nature of the classification systems provides a natural way of progressing from well-known systems and mechanisms to a vast and as-yet largely unexplored space of possible GCRs. Admittedly, even an exhaustive exploration of all possible GCR scenario configurations within the current classification system would not provide a guarantee against "black swans", but it can certainly foster a fuller understanding of the threats we face.

6. Where to next?

The classification framework presented above is dynamic, spanning a broad range of disciplines and reflecting a dense web of interacting variables along three dimensions: where critical systems are vulnerable to GCRs, how threats might spread globally, and how attempts to prevent or mitigate these threats might fail due to human factors. To successfully maintain awareness and organise the plethora of knowledge around GCRs we need to meet the following challenges:

1. collect, aggregate and digest information from highly distributed knowledge networks, overcoming communication barriers and delays;
2. update regularly the classification of GCR scenarios as knowledge advances, and as technology shapes—or is poised to shape—the relevant domains.

Meeting these challenges requires a combination of strategies. It would be sensible to populate a classification framework using a group elicitation approach, calling on experts in different critical systems, global reach mechanisms and mitigation approaches to produce short summaries containing signposts to evidence in their fields that would be relevant to GCRs. Such summaries would then be aggregated in a central repository. A group of multi-domain experts could serve as editors to make sure efforts are coordinated, language is harmonised and appropriate for an interdisciplinary audience, and credit is attributed appropriately. Similar, successful repositories for other disciplines already exist and could provide inspiration (Wolfrum, 2017; Zalta, 2016). The evolving classification system, when part of a knowledge synthesis effort, could offer a visual way to communicate the current state of knowledge (McKinnon, Cheng, Garside, Masuda, & Miller, 2015).

As the frontiers of knowledge and innovation expand, so too does the horizon of our possible futures. The framework outlined here could both inform, and be informed by, different 'foresight' tools (Cook, Inayatullah, Burgman, Sutherland, & Wintle, 2014). It may be a useful tool for generating scenarios that help us explore and prepare for new risks, emerging trends and key uncertainties. Scenarios can then be characterised in more detail and monitored using horizon scanning (Amanatidou et al., 2012; Sutherland &

Woodroof, 2009; van Rij, 2010), another tool in the 'foresight' suite. Structured horizon scanning methods could be useful to scan for the early signals of a scenario unfolding, or simply to update the classification framework with information on new discoveries, innovation, theories and data produced by the scientific community.

Globalisation and technology are advancing at a rapid pace, and it is difficult to appraise the ever-changing landscape of risks. In order for research into new, potentially disruptive technologies to proceed responsibly, and to better anticipate how interacting threats may unfold across our globe, the state of knowledge around risks and potential risk mitigation measures needs to be transparent, organised and updateable. We hope that the classification framework outlined in this paper will facilitate the communication between disciplines that such an endeavour needs.

Acknowledgements

The authors wish to thank Susan Owens, Partha Dasgupta, Danny Ralph, Martina Kunz and two anonymous referees for useful comments. This publication was made possible through the support of a grant from Templeton World Charity Foundation. The opinions expressed in this publication are those of the authors and do not necessarily reflect the views of Templeton World Charity Foundation. WJS is funded by Arcadia.

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