Systemic contributions to global catastrophic risk

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Abstract

Humanity faces a complex and dangerous global risk landscape, and many different terms and concepts have been used to make sense of it. One broad strand of research characterises how risk emerges from the complex global system, using concepts like systemic risk, Anthropocene risk, synchronous failure, negative social tipping points, and polycrisis. Another strand focuses on possible worst-case outcomes, using concepts like global catastrophic risk (GCR), existential risk, and extinction risk. Despite their clear relevance to each other, only limited connections have been made between these two strands. Here we provide a framework which synthesises the two and shows how emergent properties of the global system contribute to the risk of global catastrophic outcomes. Specifically, the global system generates hazards, amplification, vulnerability, and latent risk, as well as challenges for GCR assessment and mitigation. This systemic lens helps us understand the origins of GCR, provides a useful interface between two deeply related but infrequently connected bodies of work, and provides important insights for risk reduction.

1. Introduction

Understanding and reducing global catastrophic risk (GCR) is vital. We define GCR as the risk[1] of a catastrophic loss of life and wellbeing on a global scale, with the death of 10% or more of the current human population (Cotton-Barratt et al., 2016; Kemp et al., 2022) as a useful non-prescriptive anchoring point in terms of magnitude. Subcategories of GCR include the risk of human extinction (extinction risk), the risk of global societal collapse (collapse risk), and the risk of a wider set of catastrophes judged to be of a similar

[1] While "risk" may be conceived of in a number of different ways (SRA, 2018), here we follow previous work on GCR in focusing on the potential occurrence of certain undesirable outcomes.

magnitude as human extinction (existential risk)[2]; meanwhile, GCR is itself a subcategory of "global risk" more broadly. Hazards which could lead to global catastrophe include asteroid impacts (Baum, 2023; Mani et al., 2023), large-magnitude volcanic eruptions (Cassidy & Mani, 2022), anthropogenic climate change (Beard et al., 2021; Kemp et al., 2022), biological threats (Millett & Snyder-Beattie, 2017; Musunuri et al., 2021; Schoch-Spana et al., 2017), nuclear war (Sagan 1983; Robock 2010; Baum and Barrett 2018; Scouras 2019), and advanced artificial intelligence (Gruetzemacher & Whittlestone, 2022; Hendrycks et al., 2023; Kasirzadeh, 2024; Russell, 2019).

While these drivers are often studied in isolation, they arise as part of a complex interconnected global risk landscape. Effectively, human activities have coalesced into a vast global system involving the worldwide exchange of goods, people, information, and ideas (e.g. Helbing 2013; Centeno et al. 2015; Ellis 2015), which relies on underlying connective infrastructure (physical, digital, cultural and economic). This brings with it many benefits, but also new global hazards, vulnerabilities, and possible undesirable outcomes. Many terms and concepts have been used to describe aspects of this phenomenon, including (global) systemic risk (Centeno et al., 2015; Renn et al., 2017; Sillmann et al., 2022), compound risk (Kruczkiewicz et al., 2021), synchronous failure (Homer-Dixon et al., 2015), Anthropocene risk (Keys et al., 2019), femtorisk (Frank et al., 2014), hyper-risk (Helbing, 2013), negative social tipping points (Juhola et al., 2022; Spaiser et al., 2023), and polycrisis (Lawrence et al., 2024; Tooze, 2021).

These two strands of work — on worst-case outcomes and on the emergence of risk from the complex global system — are highly relevant to each other, yet connections have so far been limited. To rectify this, in this article we provide a framework for understanding systemic contributions to GCR. We begin by discussing "systems thinking" and why it matters for global risk, explain what we mean by "systemic contributions to GCR" and "the global system", and review relevant existing scholarship. Then, we outline our framework, which highlights five major factors: the generation of hazards, the amplification of hazards to global catastrophic outcomes, the generation of the vulnerability that leads to this amplification, the generation of latent risk, and the generation of specific challenges for successful assessment and mitigation of GCR. We discuss the insights this provides for both GCR research and the research on emergent global risk, as well as lessons for risk mitigation.

2. A systemic understanding of global risk

2.1 What is "systems thinking" and why does it matter for global risk?

"Systems thinking" recognises that a system is more than the sum of its parts (Meadows, 2008): its behaviour is emergent, and cannot be predicted purely from its constituent components. Here, we focus on complex adaptive systems (CASs), in which patterns and adaptive behaviours at higher levels emerge from localised

[2] Although specifics vary, this is the general idea underpinning much of the scholarship on existential risk (Greaves, 2024). This means that even defining existential risk requires one to make value judgments: how bad are different possible outcomes when compared to human extinction? In this article we will avoid the term "existential risk", focusing instead on GCR, extinction risk, and collapse risk. For discussions of some of the normative issues from different perspectives, we refer the reader to works by Ord (2020), Cremer and Kemp (2021), and Greaves (2024).

interactions and selection at lower levels (Levin 1998; Levin et al. 2013). Examples of CASs include ecosystems, human societies, and the Earth's biosphere (Folke et al., 2021). CASs can behave in highly nonlinear ways: large changes can have small effects, small changes can have large effects, and disruptions in one part of the system can cascade into other parts. Broadly, systems thinking allows us to make sense of such behaviours; this matters for global risk and GCR because many of the systems that humans exist within and depend on (Avin et al., 2018) are complex adaptive systems (see also section 2.2).

Our usage of "complex" here is not synonymous with "complicated" (Kreienkamp & Pegram, 2020; Snowden & Boone, 2007). A system can be complicated but not complex: this is the case if it is intricate and difficult to understand, but still largely comprehensible based on its component parts and predictable relationships between them (i.e. emergent system properties do not play an important role). A useful example of such a system is a jet engine (Kreienkamp & Pegram, 2020).

Much emergent behaviour in systems can be described using the language of feedbacks. Feedbacks occur when the state of a system affects (feeds back on) the state of that same system, either directly or indirectly. Mathematically positive feedbacks (+) are destabilising (a given change causes more of that change to occur) and mathematically negative feedbacks (-) are stabilising (the effects of a given change can be damped out). This is summarised in Figure 1, using "causal loop" and "stability landscape" diagrams. Both kinds of feedbacks can have desirable and undesirable effects: stabilising feedbacks can preserve desirable system states but also trap systems in undesirable states, while destabilising feedbacks can drive runaway evolution to desirable or undesirable system states. Most systems of interest contain multiple feedbacks, which can change in strength depending on external or internal factors, and can lead to sudden shifts in system behaviour (for example when an equilibrium state changes stability).

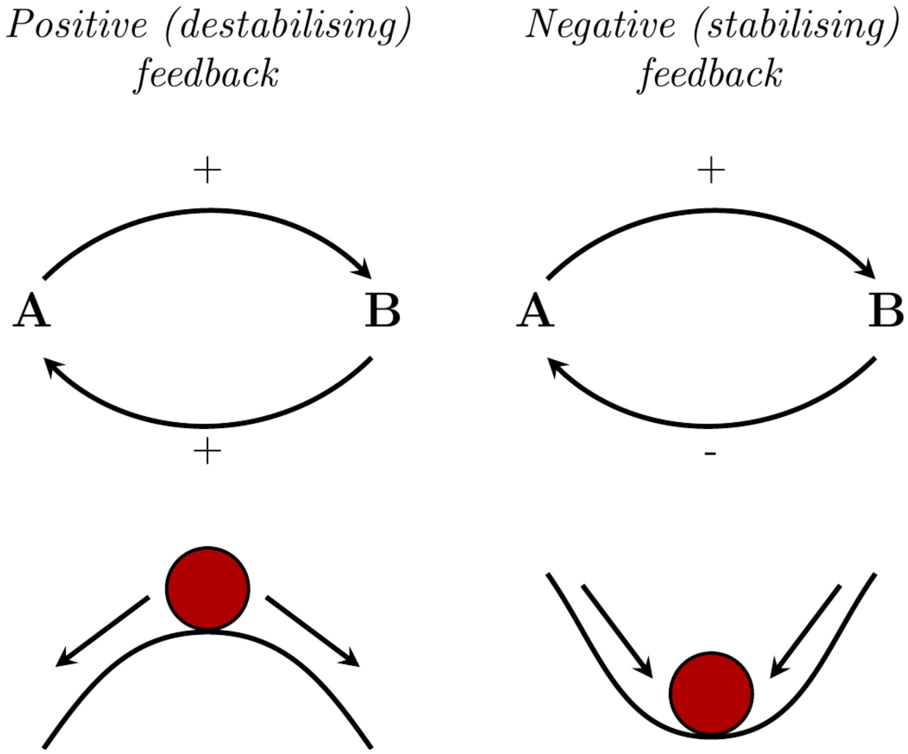

Figure 1: Summary of destabilising (mathematically positive) and stabilising (mathematically negative) feedbacks. In causal loop diagrams (top row), an arrow with a + symbol means that an increase in the first variable causes an increase in the second, and an arrow with a - symbol means that an increase in the first variable causes a decrease in the second. In stability landscape diagrams (bottom row), the state of the system is conceived of as a ball rolling on a landscape (collapsing the high-dimensional state spaces of the real world onto a single dimension). When destabilising feedbacks dominate, we see runaway change (rolling down the hill); when stabilising feedbacks dominate, the system remains within a stable equilibrium (the valley, or "basin of attraction").

Another useful framework for understanding CAS dynamics is that of resilience. While early work characterised resilience simply as the size of the system's current basin of attraction (Holling, 1973; Scheffer et al., 2001), Walker et al. (2004) define it more qualitatively as " the capacity of a system to absorb disturbance and reorganise while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks". Resilience is deeply related to adaptability (the capacity of a system to adjust its responses based on changing conditions) and transformability (the capacity to transform the stability landscape to become a new kind of system); critically, maintaining system identity at large scales under changing conditions may require radical system transformations at smaller scales (Folke et al., 2010).

2.2 The global system

To clearly describe systemic contributions to global risk, it is worth developing a notion of "the global system". By the "global system" we mean the globally interconnected system of human economic, social, political, and cultural relations, including humans themselves, material flows, and the extraction of materials from the broader Earth system. Our conceptualisation draws from both world-systems theory in the social sciences (Chase-Dunn & Grimes, 1995) and from Earth system science, where the global system has been labelled the "Anthroposphere" (Steffen et al., 2020). While the global system is a subsystem of the Earth system, the boundaries are fuzzy: the two systems have substantially shaped one another (Ellis, 2015; Frankopan, 2023; Nyström et al., 2019; Williams et al., 2015). The global system is a CAS, and so are many of its subsystems.

Why is this concept useful? For our purposes, there are two main reasons. First, by identifying a single global system within which most humans are embedded and upon which most humans rely, we can recognise that this system mediates almost all global catastrophic risk[3]. This is an important insight. Early work on GCR often treated risk as essentially synonymous to hazard: the risk *of* an asteroid impact, or the risk *of* dangerous climate change. But this neglects the important role played by vulnerability: how will the global system respond when stressed by a hazard? Foregrounding this can drastically change our understanding of GCR.

Second, identifying the global system as a CAS informs us that it will display emergent phenomena characteristic of CASs, such as nonlinear behaviour, path dependence, feedbacks, and cascading failures. We need to understand these phenomena to understand and mitigate global risk.

We will often find it convenient to say that the global system "creates" or "generates" risk. We emphasise that this is intended neither to anthropomorphise the system nor to remove culpability from individual actors (such as people, states, or corporations). For example, in the case of climate change, it is simultaneously true that a small number of companies conduct the fossil fuel extraction leading to the vast majority of carbon dioxide emissions (Carbon Majors, 2024; Heede, 2014), that these companies exist within a global geopolitical system within which it is highly profitable to extract and sell fossil fuels, and that the demand for the energy produced ultimately derives from the constrained choices of billions of individual human beings.

2.3 A wide array of concepts

There is a large body of work on how risk — or more generally, the possibility for catastrophe — emerges from the global system (i.e. arises due to its nature as a CAS); going forward, we will refer to this as "the work on emergent global risk"[4].

A natural starting point is with the concept of systemic risk. Early definitions of the term (Kaufman & Scott, 2003; OECD, 2003) emphasised the risk of an entire system failing (as opposed to part of a system failing). Subsequent work has emphasised the risk of smaller disruptions being amplified, for example due to nonlinearity, interconnectedness, and cascading failure (Centeno et al., 2015; May et al., 2008; Renn et al., 2017, 2022; Sillmann et al., 2022). The concepts of "global systemic risk" (Centeno et al., 2015; Renn et al., 2017) and "hyper-risks" (Helbing, 2013), apply these ideas specifically to the global system. Even more specifically, the concept of "femtorisk" focuses on the systemic risk due to "the actions and interactions of

[3] There are a small number of exceptions: one example is the risk posed by naturally occurring exotic physics scenarios such as vacuum collapse (Tegmark & Bostrom, 2005).

[4] While we focus on more recent work, we note that scholarship on related issues goes back many decades (e.g. Forrester, 1971; Toynbee, 1961; Wiener, 1950)

actors existing beneath the level of formal institutions, often operating outside effective governance structures" (Frank et al., 2014).

There is a wider set of related and often overlapping concepts from risk analysis, including compound risk, interacting risk, interconnected risk, and cascading risk (Pescaroli & Alexander, 2018). Although discussion of the nuances is beyond the scope of this section, we do note that the concept of compound risk — the risk of disasters involving multiple simultaneously occurring hazards (Pescaroli & Alexander, 2018; Zscheischler et al., 2018) — has recently been applied more broadly to global systems in light of the Covid-19 pandemic (Kruczkiewicz et al., 2021). If the co-occurring hazards cause more damage together than had they occurred separately, this is precisely an instance of nonlinear amplification — a key characteristic of CASs.

The global system also interacts with the global environment to produce risk. Human actions are by far the dominant driver of global environmental change (Ellis, 2015), and could trigger a wide range of ecological and environmental tipping points (Armstrong McKay et al., 2022; Barnosky et al., 2012; Richardson et al., 2023). One useful conceptual framework here is that of "Anthropocene risks" (Keys et al., 2019), which are described as originating from anthropogenic Earth system change, emerging due to the evolution of globally intertwined social-ecological systems, and involving complex cross-scale interactions.

A separate and emerging body of work applies the concept of tipping points — where a small change can have a large, abrupt, self-perpetuating, and hard-to-reverse impact — in the context of negative social change (Juhola et al., 2022; Spaiser et al., 2023). Such "negative social tipping points" are another way to understand the nonlinear creation of risk in the global system. While the focus thus far has been on stresses from anthropogenic climate change, this does not need to remain the case: tipping points in the global system could be triggered by a wide range of factors.

The subject of negative social tipping points leads us straightforwardly to collapse. Societal collapse (Brozović, 2023; Centeno et al., 2023; Tainter, 1988) likely involves interacting nonlinear processes (e.g. tipping) within the system itself (Cumming & Peterson, 2017; Juhola et al., 2022; Lenton, 2023). There is a natural intersection with the study of GCR and worst-case outcomes; in particular, a permanent global collapse is one class of catastrophes short of human extinction argued to constitute an existential risk (Belfield, 2023). A collapse is usually preceded by a crisis (Butzer, 2012).

The framework of "synchronous failure" (Homer-Dixon et al., 2015) offers a more specific causal description of how crises emerge in the modern global system. The authors first identify three important global trends: the scale of human activity, increased connectivity, and reduced diversity. They then argue that these trends favour three specific "process archetypes" — "long fuse big bang", "simultaneous stresses", and "ramifying cascade" — which interact within and across systems to produce global crises. These archetypes are relevant not just for the modern global system, but have also been applied historically, for example to the Late Bronze Age Collapse (Kemp & Cline, 2022)

Finally, the concept of polycrisis captures the general idea that the world's crises are coinciding and converging into a whole worse than the sum of its parts (Lawrence et al., 2024; Morin & Kern, 1999; Tooze, 2021). Lawrence et al. (2024) offer a more specific definition: global polycrisis is the "causal entanglement of global crises in ways that significantly degrade humanity's prospects". They describe this entanglement by distinguishing between stresses, triggers, and crises (see Section 4.2), and considering how these interact within and across systems. In this article, we typically use "polycrisis" to refer to this specific conceptual framework.

3. Systemic contributions to GCR: an analytical framework

We now provide a framework for understanding systemic contributions to GCR. Specifically, we conceptualise GCR as emerging from the global system via the generation of hazards, the amplification of hazards towards catastrophic outcomes, the generation of the vulnerability that allows for this amplification, the generation of latent risk, and the generation of specific challenges which make GCR difficult to assess and mitigate (Figure 2). The first four contributions are more direct, and the fifth is more indirect. The framework is summarised in Figure 2.

Figure 2: Systemic contributions to global catastrophic risk. The global system (Section 2.2) generates hazards, can amplify these hazards towards global catastrophic outcomes, generates the vulnerability that allows for this amplification, generates latent risk, and generates specific challenges for GCR assessment and mitigation. The first four contributions to GCR are more direct (dark red), while the fifth (challenges for GCR assessment/mitigation) is more indirect (orange). Latent risk emerges not only from the current global system but also from scenarios in which this has fully or partially collapsed; see the main text and Section 3.4.

Our focus is specifically on phenomena that arise within the global system *and* substantially require a systemic perspective (Section 2.1) to be understood. This is what we refer to as "emergent from the global system" or "generated by the global system". One partial exception is latent risk, where we also include the risk that would be produced by emergent systemic phenomena if part or all of the modern global system were to collapse (Section 3.4).

The aim here is not to provide a rigorous taxonomy: the list of contributors may not be exhaustive, and there are some conceptual overlaps. Rather, the aim is fourfold: to help us think more clearly about the systemic contributions to GCR, including where they come from and how they can be mitigated against; to ground this thinking in a fundamental recognition of the global system as a CAS; to connect work on GCR with the large body of work on how risk emerges from the global system; and to help summarise the relevant literature for others interested in these issues. While a number of GCR scholars have taken steps in this direction (Avin et al., 2018; Cotton-Barratt et al., 2020; Liu et al., 2018; Manheim, 2020; Undheim, 2024), a thorough synthesis meeting all four goals is lacking.

We now discuss these five contributors in turn.

3.1 Hazards

We define hazards as the events and processes which can serve as the proximal causes of undesirable outcomes. While early discussion of GCR often focused on exogenous hazards like asteroid impacts, many of the most concerning hazards facing humanity emerge from within the global system. For instance, anthropogenic climate change occurs due to humanity's consumption of fossil fuels. Technological as well as geopolitical developments led to the creation of nuclear weapons, the maintenance of nuclear arsenals, and thus the risk of global nuclear war. Environmental encroachment promotes the emergence of new pandemic hazards (Jones et al., 2013; Singh, 2021), and advances in biotechnology may do the same in the future (Millett & Snyder-Beattie, 2017; Musunuri et al., 2021). Despite many concerns about the societal impacts of artificial intelligence (AI), development of more and more powerful AI models is essentially racing full steam ahead, in large part due to economic and geopolitical dynamics (Brandt et al., 2022; Lee, 2018).

Why are these hazards being created? One possible answer focuses on the actions of agents. For example, Kemp (2021) has argued that a small number of "agents of doom" pursue power and profit at the expense of creating these hazards for the rest of humanity. 78 corporate and state fossil fuel producing entities are responsible for more than 70% of total cumulative carbon dioxide emissions (Carbon Majors, 2024), only nine states possess nuclear weapons (Herre et al., 2024), and only a handful of companies are currently leading the "AI arms race"[5]. Understanding how responsibility for hazard creation may be concentrated among a small number of actors is important not only for its own sake, but also for its instrumental value: it can provide important insights about ways to lower GCR (Jones, 2023).

Nevertheless, part of the problem is more pernicious: these actors exist within systems in which it makes sense — or appears to make sense — for them to create risk. Governments justify their maintenance of nuclear arsenals based on principles of strategic rationality (Amadae, 2015). Companies extract and sell fossil

[5] By "AI arms race" we mean the real or perceived race for technological superiority with respect to AI (Baum, 2020; Cave & ÓhÉigeartaigh, 2018; de Neufville & Baum, 2021); this does not necessarily imply military usage.

fuels because they can make a large profit doing so, and individuals are constrained and incentivised to consume them. One approach for describing this behaviour is using game theory: in particular, the “tragedy of the commons” highlights that it can seem individually rational to help deplete certain resources, including our collective security from global risk (Barrett, 2016; Dietz et al., 2003; Posner, 2004). However, such rational-actor narratives have their limitations, and can also serve as part of the problem, by themselves helping encourage the hazard-creating actions (Amadae, 2015).

Going a step further, the incentives for actors to create global hazards exist in part because national and international institutions have not taken effective regulatory action to prevent this. While this is in part because they themselves have little incentive to understand and prepare for large-scale unprecedented events (Posner, 2004; Wiener, 2016), it is also due to a number of other issues: some are discussed below, and others in Section 3.5. While actors remain free to create global hazards for power and profit, some will choose to do so.

Hazard-creating systems can also entrench themselves in ways that make change difficult. For example, in the case of climate change, fossil fuel companies sowed a sophisticated decades-long disinformation campaign to mislead the public (Oreskes & Conway, 2011; Supran et al., 2023). They are also supported by a range of governmental subsidies and tax incentives which actively make decarbonisation less economically feasible (Seto et al., 2016). At a systems level there are effectively stabilising feedbacks in play: the fossil-fuel-industrial complex is deeply resistant to change. Understanding these kinds of mechanisms is vital for hazard reduction.

Ultimately, these patterns of hazard creation reflect a fundamental fact about complex adaptive systems. Because selection (e.g. biological, cultural, or economic evolution) occurs at lower levels (Levin 1998; Levin et al. 2013), the behaviours which are selected for are not necessarily beneficial for the system as a whole. This has also been described using the concept of “evolutionary traps” (Søgaard Jørgensen et al., 2024). In this case, some of the selected behaviours create global hazards.

3.2 Amplification

The global system can also amplify hazards: a given hazard, or combination of hazards, may cause much more damage than naively expected. The March 2021 blocking of the Suez Canal by the container ship *Ever Given*, with consequences of billions of US dollars in lost trade income (Russon, 2021), was a clear demonstration of how the global system can amplify small stresses into much larger catastrophes. More generally, the possibility of nonlinear (i.e. disproportionate) amplification of risk by the global system or its many subsystems has been the focus of much of the work reviewed in Section 2.3 (Centeno et al., 2015; Frank et al., 2014; Helbing, 2013; Homer-Dixon et al., 2015; Lawrence et al., 2024; Renn et al., 2017, 2022; Sillmann et al., 2022; Spaiser et al., 2023).

Amplification is closely related to the concept of vulnerability, but not equivalent to it. Vulnerability is a key concept in the study of disaster risk (UNDRR, 2019), and is also important for understanding GCR (Baum, 2023; Liu et al., 2018; Mani et al., 2023); here, we use it to refer approximately to those properties of the system which determine the magnitude of the catastrophe resulting from a given hazard or combination of hazards[6]. We find it useful to treat amplification and vulnerability separately: we discuss vulnerability (and emergent trends in vulnerability of relevance to GCR) at greater length in Section 3.3.

For a simple conceptual understanding of amplification in the context of GCR, we again consider the simple metaphor of a ball in a stability landscape (Figure 3). We conceive of the global system as existing in a state of dynamic quasi-equilibrium: it is constantly evolving, yet its basic function and structure persists, and minor shocks can be recovered from. Yet other possible system states exist, some of which would constitute global catastrophic outcomes. Hazards (Section 3.1) can push the system out of its current basin of attraction towards one of these (normatively) worse states, whereupon the effect of the hazard is amplified by feedbacks internal to the system. Vulnerability enters this picture in multiple ways: how shallow is the original basin of attraction (how weak are the initial stabilising feedbacks), how strong are the feedbacks driving the system to the new outcome, and how severe (i.e. normatively bad) is the new outcome? The concept of resilience also relates to the depth of the original basin of attraction, but in the opposite direction: here, a decrease in resilience is an increase in vulnerability.

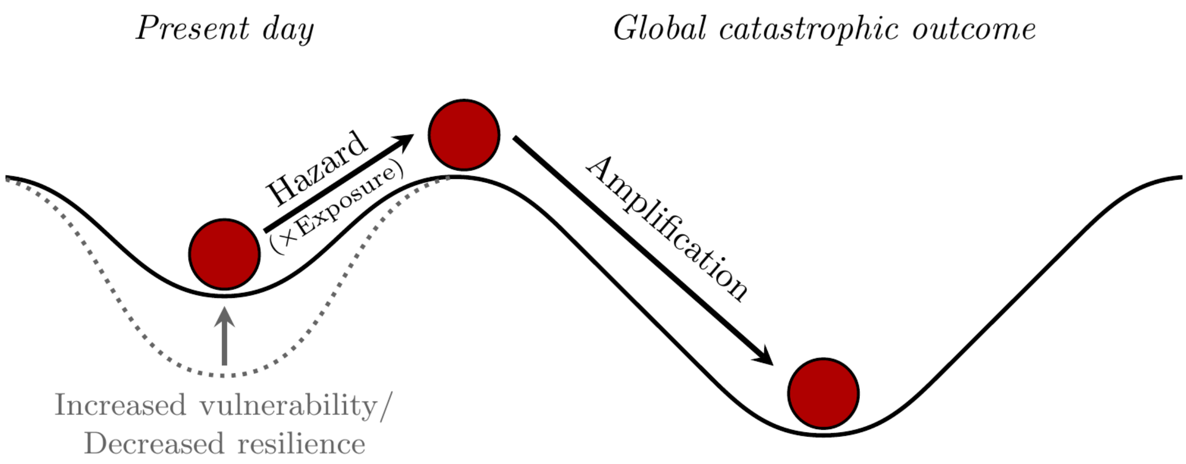

Figure 3. Hazard, vulnerability, amplification, and global catastrophic outcomes. Hazards (modulated by exposure) threaten the system's persistence in its current basin of attraction, and can set in motion runaway evolution towards global catastrophic outcomes (amplification). Vulnerability enters the picture in multiple ways: how deep are the two basins of attraction, and how bad is the global catastrophic outcome? We emphasise that this picture is vastly oversimplified (see text), but it captures important elements of the problem.

This picture is of course an oversimplification. There are many kinds of possible global catastrophic outcomes, many possible pathways to them, and the degree of amplification will vary based on the specific

[6] In the study of disaster risk, risk is often framed as the result of hazard, vulnerability, and exposure (UNDRR, 2019). Exposure is an important concept for natural disasters because those tend to be localised: for example, earthquakes have very different impacts depending on how close they occur to human settlements. However, exposure may be less important a concept for global catastrophic risk, since most humans are often exposed by definition. For the purposes of this article, we take a broad view of vulnerability in which it includes those properties of the global system which can transform exposure from local to global, for example when air travel allows a localised pandemic (local exposure) to quickly travel around the world (global exposure).

case. Figure 3 depicts amplification as occurring via a tipping point[7], but this does not need to be the case: nonlinear amplification can also occur without tipping points. Amplification can also occur when multiple co-occurring hazards cause more damage together than they would have separately, or when one hazard triggers another hazard. The key point is that emergent nonlinearity in complex adaptive systems can lead to an amplification of hazards. Figure 3 highlights this and also allows us to make important conceptual connections.

Amplification would play an important role in a wide range of global catastrophe scenarios. The impacts of natural hazards like asteroid impacts and volcanic eruptions would be amplified through their effects on global critical infrastructure (Baum, 2023; Mani et al., 2023; Moersdorf et al., 2023); indeed, the clustering of such infrastructure near centres of volcanic activity vastly amplifies the risk even from lower-magnitude volcanic eruptions (Mani et al., 2021). As the Covid-19 pandemic has illustrated, the impact of novel infectious diseases can be vastly amplified by global transit networks (Baker et al., 2022) as well as by follow-on economic and social disruption. The worst outcomes from climate change will likely not arise directly due to increased temperatures, but rather indirectly through phenomena like conflict, famine, and mass displacement (Beard et al. 2021; Richards et al. 2021; Kemp et al. 2022; Arnscheidt et al., under review). The effects of nuclear war could be amplified by subsequent global cooling, leading to large-scale global starvation (Xia et al., 2022). Developments in AI capabilities could be amplified towards catastrophic outcomes well before the emergence of artificial general intelligence, for example via societal and economic destabilisation (Kasirzadeh, 2024) and interactions with biological and nuclear risk (EBRC, 2023; Hendrycks et al., 2023; Maas et al., 2023)

The work on emergent global risk (Section 2.3) helps us understand further details of how the global system can amplify hazards. Amplification on networks can be understood in terms of contagion and cascading failure (Helbing, 2013; Krönke et al., 2020; Newman, 2018), and has played a key role in conceptualisations of global systemic risk (Centeno et al., 2015). Many of the amplifying effects alluded to in the above paragraph result from nonlinear social dynamics (e.g. Schelling, 1978), and could be understood in terms of social tipping points with negative outcomes (Juhola et al., 2022; Spaiser et al., 2023). We briefly note that such amplifying social dynamics can include human responses to hazards: as one example, trade restrictions in response to global food price shocks usually increase prices further (Alexander et al., 2023; Clapp & Moseley, 2020). In practice, amplification would involve a complicated web of nonlinear change within systems as well as interactions between systems. Approaches such as the stress-trigger-crisis model of Lawrence et al. (2024) or the earlier causal archetypes of the "synchronous failure" model (Homer-Dixon et al., 2015) could prove very helpful in understanding this (Section 4.2).

One particularly severe outcome of amplification in the context of GCR could be global societal collapse. While there are many ways to define the latter, one simple, forward-looking option in our case is a rapid development of the global system towards a state where it is no longer able to provide (as it currently does)

[7] Specifically, it depicts amplification as occurring once the system passes across the top of the hill, which represents an unstable equilibrium state. This is technically an instance of "noise-induced tipping" (Ashwin et al., 2012); for an accessible explanation in terms of stability landscapes, see Lenton (2023).

for the material subsistence of most humans[8]. It is unclear whether such a collapse could be recovered from (Baum et al., 2019; Belfield, 2023). There has been much work on the subject of collapse, most notably in the case of past societies (Brozović, 2023; Centeno et al., 2023; Tainter, 1988) but also in ecology (Cumming & Peterson, 2017) and in complex evolutionary systems more generally (Arnscheidt & Rothman, 2022). While a wide range of possible mechanisms has been identified, one key consensus matters for our purposes: collapse may be set in motion by a particular stressor (i.e. hazard), but ultimately plays out due to feedbacks and mechanisms internal to the system (i.e. vulnerability and amplification).

3.3 Vulnerability

In the context of GCR, vulnerability is also emergent from the global system. This is well understood by the the literature on emergent global risk, which argues that (at least in some sense) there is a greater potential for amplification in the global system than there used to be (Centeno et al., 2015; Helbing, 2013; Homer-Dixon et al., 2015; Lawrence et al., 2024). The severity of possible outcomes may also be worse now than in the past; while the emergence of new and dangerous technologies (i.e. hazards) has played a role in this (Ord, 2020; Rees, 2004), so too has the fragility and potential irreplaceability of global critical infrastructure (Manheim, 2020). Here, we frame our analysis around three key related trends: increased global interconnectedness, decreased global diversity (in a variety of domains, and particularly in terms of possible responses to disruptions), and humanity's reliance on advanced technology as well as complex sociotechnical systems.

The trend of increasing global interconnectedness is readily apparent. For example, global food trade flows have increased substantially in the last few decades (D'Odorico et al., 2018; Puma et al., 2015), and the yearly number of air traffic passengers doubled from 2 to 4 billion between 2000 and 2019 (facilitating the potential spread of pandemics; see e.g. Baker et al. 2022). Increased interconnectedness in the modern global system is typically identified as a major driver of amplification and global systemic risk (Centeno et al., 2015; Helbing, 2013; Homer-Dixon et al., 2015; Lawrence et al., 2024; Sillmann et al., 2022). Interconnectedness decreases a system's susceptibility to smaller shocks, by allowing the flow of resources to make up for localised shortfalls, but increases its susceptibility to larger disruptions, by allowing failures to cascade (Foti et al., 2013; Helbing, 2013; Scheffer et al., 2012; Young et al., 2006). An illustrative thought experiment is the following (Siegenfeld & Bar-Yam, 2020): imagine you have 100 ladders leaning up against a wall, and then you tie them all together. Each individual ladder is much less likely to fall, but if they do fall they will all fall at once.

A second important trend affecting vulnerability is a loss of global diversity. This has been occurring in a wide range of contexts, from language to institutions to biology (Young et al., 2006). One specific instructive example is in the global food system: food production is increasingly reliant on a small number of staple grain species, dominated by a small number of companies, and dominated by a small number of countries (Clapp, 2023; Nyström et al., 2019). This allows for greatly increased short-term productivity, but makes us

[8] This is not to suggest that the maintenance of the global system in its current state is normatively desirable. However, a failure of this system to provide for large-scale human subsistence, with no immediate alternatives available, would result in death and suffering on a vast scale.

more vulnerable should conditions suddenly change: for example, what happens if one of these staple grain species or key global suppliers fails for some reason? More generally, the loss of diversity is an issue because diversity is part of how complex adaptive systems retain resilience (Levin 1998; Folke et al. 2004; Levin et al. 2013). A particularly useful framing is that of response diversity: maintaining a variety of potential response behaviours provides complex systems — including the global system — with the "raw material" for adaptive capacity after disruptions (Walker et al., 2023).

A third key trend is humanity's increasing reliance on advanced technology — and indeed, on complex sociotechnical systems (composed of humans and their interactions with technology) which no individual human fully understands. Returning to the food system example, developments in industrial agriculture (breeding new high-yield crop strains, large-scale fertiliser production, machinery) vastly increased global yields throughout the 20th century (Evenson & Gollin, 2003; Smil, 2004); yet, most humans now depend on these technologies for their survival (Moersdorf et al., 2023). Greater integration of AI into agricultural systems (Galaz et al., 2021; Tzachor et al., 2022) will amplify this dependence. In practice, we depend not just on the advanced technologies themselves but also on the increasingly complex sociotechnical systems within which the technologies are manufactured, distributed, and used. Sociotechnical complexity, despite its other benefits, sets us up for hard-to-prevent cascading failures (Perrow, 1999). More critically, increases in complexity are often irreversible, as important infrastructure and knowledge pertaining to older approaches is lost (Manheim, 2020) — increasing the severity of the worst-case outcomes.

Of course the above trends have also brought substantial benefits. Beyond the other benefits of globalisation, increased interconnectedness reduces the risk of smaller disruptions. Reduced diversity and advanced technology both allow for increased productivity and efficiency under a specific set of circumstances, and thus plausibly also help the global system buffer against certain smaller shocks. Yet, despite these benefits, we suggest that each of these three trends increase the likelihood and potential severity of global catastrophic outcomes. Interconnectedness allows failure to spread much more quickly to larger scales, and a lack of diversity means the global system will struggle to adapt to certain unexpected disruptions. The dependence on technology means that scenarios involving some loss or failure of this technology lead to much more catastrophic outcomes than they otherwise would.

If our vulnerability in the context of GCR has indeed been increasing, why is this? At one level of explanation, we can highlight economic incentives to prioritise efficiency (short-term reliable productivity) over resilience. This is particularly apparent in ecosystem management, where there is a long history of humans attempting to "optimise" an ecosystem (e.g. for productivity) and later finding, often at great cost, that key elements of resilience were lost in the process (Holling & Meffe, 1996; Scott, 1998). For much the same reasons which lead to insufficient governance of hazard-creating actors (see Section 3.1), there is insufficient governance of vulnerability-creating actors. As long as these actors (individuals, companies, or states) can obtain a short-term gain from actions that increase global vulnerability (prioritising efficiency over resilience), they will do so.

Yet, things are also more complicated. Many of the key factors driving global vulnerability — including the three trends outlined above, are ultimately emerging in a complex decentralised manner. As one additional example, the fact that our complex global infrastructure can develop highly connected hubs which propagate disruptions (e.g. Mani et al., 2021) is due to fundamental aspects of bottom-up network development, such as preferential attachment (Newman, 2018), which are very difficult to avoid. Nevertheless, governments and global institutions can proactively invest in resilience, for example by investing in and promoting response diversity (Walker et al., 2023), actively maintaining backups for key critical infrastructure systems, carefully modularising those systems, and so on.

Ultimately, much like the emergent generation of hazards, the generation of vulnerability is a deep consequence of the fact that selection in complex adaptive systems occurs at lower levels (Levin 1998; Levin et al. 2013) and is thus not necessarily to the benefit of the system as a whole.

3.4 Latent risk

Another perhaps more easily overlooked systemic contribution to GCR involves latent risk. Latent risk refers to risk that is dormant under one set of conditions but becomes active under another (Kemp et al., 2022; Tang & Kemp, 2021). One illustrative example of latent risk on a global scale is the following (Tang & Kemp, 2021): while stratospheric aerosol injection (SAI) could cool the planet and potentially reduce global warming, it also introduces the risk of "termination shock", in which the planet warms very quickly if aerosol injection were to suddenly stop (Parker & Irvine, 2018). This is a latent risk because it only becomes active once SAI is deployed, but exists independently of whether SAI turns out to be beneficial for humanity or not.

The global system is actively generating latent risk. For example, beyond its immediate impacts, climate change could hamper humanity's ability to recover from other catastrophes (Kemp et al., 2022). More generally, if any of the global critical systems which humanity depends on were to fail, this might trap us in a state where that system could not be regenerated, and would also decrease our species' resilience to further catastrophes, such as human extinction. If increasing sociotechnical complexity leads to the loss of simpler alternatives (Manheim, 2020; see also Section 3.3), this plausibly exacerbates the latent risk in such scenarios. To illustrate these issues while maintaining a focus on the worst-case outcomes, we now consider how systemic latent risk would manifest after global societal collapse (noting that any reasoning about post-collapse worlds is necessarily speculative).

After a collapse, systemic phenomena might trap the system in the collapsed state. Various theories of human civilisational development — i.e., the development of the global system — emphasise the role of amplifying feedbacks. For example, the industrial revolution may have been substantially driven by feedback cycles that rapidly increased human access to energy (Lenton & Scheffer, 2024). However, if the global system were to collapse and advanced technology were to be lost, it is not clear that this pattern could be repeated, because most easily accessible fossil fuel will have been used up (Baum et al. 2019; Belfield 2023)[9].

[9] We note that there are other factors which point in the opposite direction: for example, metals would be much more easily accessible in a post-collapse world than earlier in Earth history, because they could be scavenged from the ruins of cities (Baum et al. 2019; Belfield 2023).

If amplifying feedbacks initially propelled the global system to its present state, the lack of such feedbacks — and thus, a dominance of stabilising feedbacks — could prevent re–industrialisation after a collapse.

After a collapse, systemic phenomena could also substantially increase the risk of human extinction. Without industrial methods of food production, global population would fall to a substantially lower level and may also become geographically disconnected. Surviving human populations could then face nonlinear ecological dynamics akin to those faced by non-human species (e.g. May, 1977; Scheffer et al., 2001), including runaway extinction if population numbers fall below a minimum size[10]. Crucially, minimum viable population sizes are often set by the influence of population size on the ability to effectively cooperate (Stephens & Sutherland, 1999), and may thus be much higher than those predicted purely on the basis of genetics (e.g. Baum et al., 2019). While complete human extinction remains a high bar, one key point is worth emphasising: because of latent risk and systemic phenomena, a given catastrophe does not need to make Earth completely uninhabitable to ultimately lead to human extinction.

3.5 Challenges for GCR assessment/mitigation

Finally, the global system generates emergent challenges for GCR assessment and mitigation, which indirectly increase GCR. GCR is also difficult to assess and reduce for reasons that have little to do with the global system — for example, there are fundamental methodological challenges associated with studying unprecedented, high-impact, and potentially existential events (Beard et al., 2020) — and these are not our focus here. Instead, we highlight challenges that arise specifically due to the structure of the global system and its nature as a CAS.

Emergent complexity makes it impossible to understand the full state of the global system (i.e. its interconnections, structures, dependencies); to the extent to which GCR emerges from this complexity, this makes it more difficult to understand GCR. Again, “complex” should be distinguished from “complicated”: systems with only the latter property are ultimately fully knowable and manageable in a top-down manner, while those with the former are not (Kreienkamp & Pegram, 2020). When the impossibility of knowing the full system state is combined with the possibility for sudden nonlinear disruption, we further find that abrupt surprises are to be expected (Duit & Galaz, 2008; Siegenfeld & Bar-Yam, 2020). With respect to GCR, this puts us fundamentally into the realm of “deep uncertainty” (Walker et al., 2013), where we know (or can agree on) neither the full set of possible outcomes nor their likelihoods. Complexity and deep uncertainty fundamentally challenge existing risk assessment and governance paradigms (Currie, 2019; Duit & Galaz, 2008; Kreienkamp & Pegram, 2020; Schweizer, 2021).

The complex structure of the global system also makes it difficult to mitigate against GCR. For example, the relatively decentralised nature of the international system leaves us with profound governance gaps regarding both GCR and global systemic risk (Goldin & Vogel, 2010; Kemp & Rhodes, 2020), coordination problems, and a lack of identifiable risk owners. Top-down control is not necessarily better: existing top-down paradigms and institutions also struggle to govern systemic contributions to GCR (Kreienkamp

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[10] For a brief discussion of minimum viable human population sizes in the context of a post-collapse world, see Baum et al. (2019)

& Pegram, 2020; Sundaram, 2023). Any system created to help govern the complexity becomes a part of the complexity (Fisher & Sandberg, 2022), with a non-zero chance of making things worse. As noted previously, beyond our own individual biases, our governing institutions are structured such that there are strong incentives to undervalue GCR mitigation, for example due to short political time horizons (Posner, 2004; Wiener, 2016).

Developing comprehensive solutions to the above issues is a huge challenge; nevertheless, there are some brief points we can make. First, we need better methods for assessing and forecasting under deep uncertainty: structured democratic methods and collective intelligence may be useful here (Cremer & Whittlestone, 2021; Yang & Sandberg, 2023). Second, and perhaps more fundamentally, we need to recognise the weaknesses of the "legacy toolkit" of top-down planned management for governing complexity, and that the traditional goals of certainty and control are not attainable. Instead, governance should be more dynamic, flexible, and adaptive: others have provided a number of recommendations for achieving this (Duit & Galaz, 2008; Fisher & Sandberg, 2022; Kreienkamp & Pegram, 2020). Filling the governance gaps (Goldin & Vogel, 2010; Kemp & Rhodes, 2020) is another clear priority.

4. Discussion

4.1 A better understanding of GCR

The framework we have presented helps us better understand GCR, in a number of ways. Perhaps most fundamentally, building on earlier work (Liu et al., 2018), it makes clear that GCR is composed of much more than hazards. Much GCR literature has tended to implicitly conflate hazard and risk: this is typically apparent in any list of "global catastrophic risks" (e.g. Bostrom & Cirkovic, 2008; Cotton-Barratt et al., 2016). While focusing on hazards was useful in early GCR work, this critically neglects amplification, vulnerability, and so on. A useful (though non-absolute) heuristic may be to say that we face global catastrophic risk — not risks — and that the various things we are concerned about are those which contribute to this overall risk.

Building on this, our framework provides one way to think about systemic contributors to risk beyond hazards. There are other ways to do so, for example in terms of hazard, vulnerability and exposure (Liu et al., 2018); in terms of the critical systems affected, spread mechanisms, and prevention and mitigation failures (Avin et al., 2018); and in terms of prevention, response, and resilience failures (Cotton-Barratt et al., 2020). All of these frameworks complement each other. Advantages of our framework include: the focus on amplification, which allows for a clearer connection to the literature on emergent global risk (Section 2.3; see also Section 4.2), the focus on the origins of global vulnerability, the fundamental grounding in CAS theory, and the inclusion of latent risk.

More specifically, the framework can be used to structure thinking about the sources and mitigation of GCR. GCR can be reduced by reducing the probability or magnitude of hazards (as noted by much other work), reducing the potential for amplification, avoiding the emergence of vulnerability in the first place, reducing latent risk, and developing better methods and institutions for GCR assessment and governance under complexity. The framework could thus be used to categorise and generate specific interventions for GCR mitigation: this is a useful direction for future work.

4.2 The emergence of GCR from the global system

A second contribution of this framework is in thoroughly connecting the literature on GCR with the literature on how risk and catastrophe emerges from the global system (e.g. Section 2.3). Our framework could serve as a useful interface between the two bodies of work and their respective research communities.

While the principal difference is clearly our explicit focus on worst-case outcomes, it is instructive to note which parts of our framework overlap with existing work on emergent global risk, and which do not. Chief among the overlaps is amplification: for example, this is a major focus of systemic risk (Centeno et al., 2015; Renn et al., 2017, 2022; Sillmann et al., 2022), hyper-risk (Helbing, 2013), femtorisk (Frank et al., 2014), synchronous failure (Homer-Dixon et al., 2015), polycrisis (Lawrence et al., 2024) and negative social tipping points (Juhola et al., 2022; Spaiser et al., 2023). There is also productive synergy with respect to the assessment and governance challenges, which have been discussed both with and without reference to GCR (Duit & Galaz, 2008; Fisher & Sandberg, 2022; Goldin & Vogel, 2010; Kreienkamp & Pegram, 2020; Levin et al., 2013; Schweizer, 2021). The deep trends in vulnerability are less often a focus; key exceptions include synchronous failure and polycrisis (Homer-Dixon et al., 2015; Lawrence et al., 2024), as well as in the literature on resilience (e.g. Nyström et al., 2019). Interestingly, the emergent generation of hazards that are not climate change has rarely been addressed (a notable recent exception is the work by Søgaard Jørgensen et al., 2024), and the same is true of latent risk: these two areas could thus pose particularly useful directions for future research.

Our framework also has a number of key limitations. For example, while the focus on the global system is useful and provides important insights, the different subsystems of the global system are unlikely to each contribute equally to GCR, and future work should consider this more explicitly. Second, the very framing of risk as instantiated by some hazard which occurs with some probability (even with amplification, vulnerability, and important systemic phenomena included) can still struggle to capture the complex causal webs that may be responsible for GCR. This is the case, for example, if hazards interact, trigger each other, and/or are slow-moving.

Recent work on polycrisis (Lawrence et al., 2024) provides an ambitious conceptual framework that could help with some of these issues. In particular, Lawrence et al. introduce their stress-trigger-crisis model (conceptualised similarly to Figure 3) in which slow stresses destabilise a system, triggers push it out of its basin of attraction, and crises occur when the system is on the cusp of exiting the basin. Each of these factors can interact within and across different systems — providing a conceptual means to understand how various subsystems of the global system interact to generate GCR. Their focus on "the realization of chains of cause and effect that cause harms", rather than on risk, may further help to overcome the second limitation described above. However, we note that in the case of GCR, it is in part the focus on risk which allows us to speak with clarity about possible worst-case outcomes — and, if preventing such outcomes is a priority, it is critical that we are able to do so.

4.3 Systems-informed mitigation: leverage points for reducing GCR

With all this knowledge in hand, how best to reduce GCR? Beyond what we have already discussed (e.g. in Section 4.1), systems thinking has another critical insight to offer us: leverage points (Meadows, 2008). Essentially, the possibility of nonlinear change in the complex global system also cuts in a positive direction: the right intervention, in the right place, could plausibly have an outsized impact in terms of reducing GCR.

This idea has been increasingly applied in the context of climate change and the transition to a zero-carbon economy. Two framings are those of "sensitive intervention points" (Farmer et al., 2019) and "positive tipping points" (Lenton et al., 2022; Otto et al., 2020; Winkelmann et al., 2022). While the latter concept is potentially more restrictive (not all instances of nonlinear change are appropriately categorised as "tipping"), it has the advantage that there could be "early opportunity signals" that such a transition is possible (Lenton et al., 2022). Critically, tipping points (and leverage points more broadly) could be upward-scaling (Sharpe & Lenton, 2021), allowing for substantial change even in highly decentralised situations or to be driven by actors conventionally deemed as less powerful.

We suggest that applying these concepts to GCR reduction — identifying, categorising, and activating potential leverage points for the reduction of GCR — should be a major priority for future research. Although a synthesis across the different key risk drivers is currently lacking, the framing of identifying particularly effective intervention points has already been used in the context of GCR: one recent example highlights access to computational power ("compute") as a key point of leverage in AI governance (Sastry et al., 2024)

4.4 Policymaking for systemic GCR reduction

A systemic understanding of GCR provides some important insights for policymaking; here, we briefly summarise a few key points. As discussed in Section 4.1, it is essential to broaden the assessment of risk beyond hazards, and not to conflate the two. Next, attempts to govern GCR must take into account the global system's nature as a CAS (Section 3.5). This includes recognising deep uncertainty and employing better methods for understanding GCR, as well as developing governance institutions which are more dynamic, flexible, and adaptive. A focus on resilience — specifically, resilience to global catastrophic hazards and/or outcomes — will be key. Identifying and activating leverage points (Section 4.3) could be helpful in implementing the required changes. Governments and intergovernmental institutions could set up central risk offices to act as risk owners, monitor contributors to GCR, conduct comprehensive risk assessments, and (democratically) plan responses. Importantly, GCR cannot be left ungoverned (as it currently largely is, see e.g. Kemp & Rhodes, 2020), and the hazard-creating actors (Section 3.1) should be democratically reined in.

5. Conclusion

We face a complicated, complex, and dangerous global risk landscape. Much of what we need to worry about — regardless of whether we frame things in terms of risk, crisis, or catastrophe — emerges due to systemic phenomena. The global system generates hazards, can amplify these hazards into much larger catastrophes, generates the vulnerability that allows for this amplification, generates latent risk, and provides specific challenges for GCR assessment and mitigation (Section 3). The framework presented in this article helps us better understand GCR and how to mitigate it (Sections 4.1 and 4.3); connects literature on GCR with the large body of work on emergent global risk, pointing at useful paths forward (Section 4.2); and yields valuable insights for policy (Section 4.4). While much remains to be done to assess and reduce GCR, we hope that this article will serve as a useful guidepost in such efforts.

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C.W.A. conceptualised and wrote the paper with input from all authors. All authors contributed to the text of the final article.

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Conflicts of interest

A.M. is a UKRI Policy Fellow seconded to the Department for Science, Innovation and Technology. The views and conclusions contained herein are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Department for Science, Innovation and Technology or the UK Government.

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