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Article

Adaptation to and Recovery from Global Catastrophe

Timothy M. Maher Jr. [1,2,*] and Seth D. Baum [1]

1 Global Catastrophic Risk Institute, P.O. Box 85561, Seattle, WA 98145-1561, USA; E-Mail: seth@gcrinstitute.org

2 Bard College Center for Environmental Policy, 30 Campus Rd, Annandale-on-Hudson, NY 12504-5000, USA

* Author to whom correspondence should be addressed; E-Mail: tm9125@bard.edu; Tel.: +1-314-599-3083.

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Abstract: Global catastrophes, such as nuclear war, pandemics and ecological collapse threaten the sustainability of human civilization. To date, most work on global catastrophes has focused on preventing the catastrophes, neglecting what happens to any catastrophe survivors. To address this gap in the literature, this paper discusses adaptation to and recovery from global catastrophe. The paper begins by discussing the importance of global catastrophe adaptation and recovery, noting that successful adaptation/recovery could have value on even astronomical scales. The paper then discusses how the adaptation/recovery could proceed and makes connections to several lines of research. Research on resilience theory is considered in detail and used to develop a new method for analyzing the environmental and social stressors that global catastrophe survivors would face. This method can help identify options for increasing survivor resilience and promoting successful adaptation and recovery. A key point is that survivors may exist in small isolated communities disconnected from global trade and, thus, must be able to survive and rebuild on their own. Understanding the conditions facing isolated survivors can help promote successful adaptation and recovery. That said, the processes of global catastrophe adaptation and recovery are highly complex and uncertain; further research would be of great value.

Keywords: risk; catastrophe; recovery; civilization; futures; resilience; expected value; space colonization; adaptation; preparation

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1. Introduction

How sustainable is human civilization in the wake of global catastrophes? This is the question we seek to address in this paper. The global catastrophes we have in mind are specifically those that would cause massive destruction across the planet without causing outright human extinction. Pandemics, nuclear wars and ecological collapses are among the possible global catastrophes. A growing body of literature examines these catastrophes, their impacts and how to prevent them [1–11]. However, there has been relatively little attention to how human survivors could avoid extinction, adapt to post-catastrophe conditions and work towards recovering civilization. There has been similarly little attention to what humanity can do now, prior to catastrophes, in order to help survivors succeed [12]. Given the goal of avoiding human extinction and sustaining human civilization, these topics deserve consideration alongside studies of characterizing and preventing catastrophe.

How humans may adapt to and recover from global catastrophe can be a challenging topic to study. One reason is the unprecedented nature of the events in question. While there have been many global catastrophes, such as World Wars I and II and the 1918 flu, no catastrophe has ever come close to shutting down the entirety of global civilization. Thus, we cannot learn what would happen from experience or empirical observation of prior global catastrophes. Perhaps the closest call came 73,000 years ago after the Toba volcano eruption [13], which may have reduced the human population to mere thousands of individuals [14]. However, recent archaeological finds suggest the catastrophe may not have been so severe [15]. Even if Toba did threaten humanity's survival, it came long before modern civilization and, thus, may be of limited relevance to present catastrophes. Also, it occurred so long ago that it is difficult to know what happened.

Another challenge is the highly complex nature of the events. Outcomes likely depend on both environmental and human factors. The catastrophe itself could leave behind damaged environments, such as nuclear war leaving behind radiation from nuclear weapons and dimmed skies from the ashes of burned cities. The effects could have many human consequences in everything from physical infrastructure to mental health. Studying such complex environmental-social systems is challenging enough for present times, when the systems can be directly observed, or for "normal" future conditions, when present trends can be extrapolated. For unprecedented global catastrophe scenarios, the challenge is even greater, and so, a healthy dose of humility is warranted.

That said, we believe that some insight can be gained from careful study. Local-scale historical analogs often exist, such as nuclear weapons testing and use in Hiroshima and Nagasaki, local natural disasters and societies that have collapsed. Some global-scale analogs can also be found, such as volcanic eruptions that help us understand nuclear winter. With care, these analogs can be applied to global catastrophes. For example, some global catastrophe scenarios (e.g., nuclear war) could result in small survivor communities clustered in rural areas, disconnected from a global economy and unable to use modern technology. Such scenarios could resemble isolated, low-technology communities of the past and present.

Additionally, other research can identify complex patterns of vulnerability and resilience within social-ecological systems that may lead to either the destabilization and collapse of the civilization or stabilization and possible long-term recovery [16,17]. This research examines the social and environmental stressors that may have led to historical periods of catastrophic collapse. Identifying ways in which previous societies have adapted to common social and environmental stressors and recovered from catastrophes can help guide us to prepare future catastrophe survivors to increase their likelihood of recovery.

In this paper, we develop the concepts of global catastrophe adaptation and recovery and analyze how they could proceed. Section 2 discusses the importance of global catastrophe adaptation and recovery from both anthropocentric and ecocentric ethics perspectives. The success of global catastrophe adaptation and recovery is tied to the long-term outcomes of humanity, Earth-life and even life in the universe. Section 3 explores the processes of global catastrophe adaptation and recovery. This discussion inevitably only scratches the surface of these highly complex processes, and so, the section also discusses several lines of existing research that could be drawn on to advance the study of global catastrophe adaptation and recovery. Section 4 goes into detail on one relevant line of research, that of resilience theory. Resilience theory provides a powerful framework for analyzing socio-ecological systems and has already been applied at length to local catastrophes; this research has a lot to offer to the study of global catastrophe adaptation and recovery. Section 5 presents a resilience-based method for analyzing global catastrophe adaptation and recovery, focusing on the environmental and social stressors posed by the catastrophe scenario. This method can be used to identify steps that can be taken now, prior to global catastrophe, in order to promote the success of adaptation and recovery. Section 6 concludes.

2. Importance of Global Catastrophe Adaptation and Recovery

Before diving into the details of how global catastrophe adaptation and recovery could proceed, it is worth pausing to consider why this is an important topic to study. In short, the process could be a crucial part of the ultimate outcome of human civilization, of life on Earth and even of the entire universe. What qualifies as important is ultimately an ethical question. We analyze the importance of global catastrophe adaptation and recovery from both anthropocentric and ecocentric consequentialist ethics frameworks. For simplicity, we use universalist ethics, *i.e.*, ethics that value everyone or everything the same across space and time [18], instead of frameworks that use discounting or other means of weighting some things more than others.

Some insights from astrobiology—the study of life in the universe—can be helpful here [19]. In approximately one billion years, the Sun transitions into the Red Giant phase of its lifecycle, increasing in luminosity and pushing the inner limits of our solar system's known habitable zone past Earth's orbit [20–22]. When this happens, life on Earth as we know it can no longer exist. It is not clear exactly when Earth will become uninhabitable, in part because of the possibility of other forms of life evolving. However, what is clear is that at some point, all life on Earth will die out. Unless Earth-life can spread beyond its home planet, its existence will end. Meanwhile, if Earth-life can successfully colonize other places, then it can continue to exist for much, much longer.

The colonization of space by Earth-life may well be possible. Indeed, humans are already conducting manned and robotic missions of our home planet, all within 110 years of the first plane flight. At this rate, the astronautics advances necessary for space colonization could be feasible within the one billion or so years in which Earth remains habitable. However, space colonization requires the leadership of a technological civilization along the lines of what humanity—and only humanity—has today. Potentially, some other species could eventually develop the capacity to colonize space. It is difficult to say what the odds of that occurring are. Barring that possibility, then, the fate of all Earth-life in the universe depends on the availability of technological human civilization to lead space colonization. Since Earth-life may be the only life in the universe [23], that means that the fate of life in the universe could hinge upon whether human civilization successfully colonizes space. This makes the survival of technological human civilization to be of utmost importance from both utilitarian [24] and ecocentric [25] ethical perspectives.

There are two ways to sustain technological human civilization. First, one can prevent global catastrophes from occurring. This is the approach emphasized in most studies of global catastrophic risk [2–11]. Second, one can prevent global catastrophes from ending technological human civilization by enabling catastrophe survivors to adapt to post-catastrophe conditions and to then recover civilization. That is the approach taken here. In focusing on post-global catastrophe success, we do not mean to diminish the importance of preventing global catastrophe. To the contrary, we believe that prevention is very important, perhaps even more important, since even a survivable global catastrophe would still be tragic. However, adaptation to and recovery from global catastrophe is clearly important, too, and deserving more attention than it has been receiving.

Figures 1 and 2 show some possible trajectories for human civilization in terms of some measure of anthropocentric value (Figure 1) and ecocentric value (Figure 2). Potential trajectory curves are labeled alphabetically, with the same labels applied to both figures. We emphasize that the trajectories shown here are rough sketches not drawn to scale and should not be interpreted as being precise. They are also not the only possible trajectories. They are drawn to illustrate the importance of space colonization, global catastrophe, recovery and adaptation in terms of anthropocentric and ecocentric value.

Figure 1. Rough sketches of several possible trajectories for human civilization, measured in anthropocentric value. Curves are labeled alphabetically and are also not drawn to scale. Curve B is intentionally labeled twice for clarity.

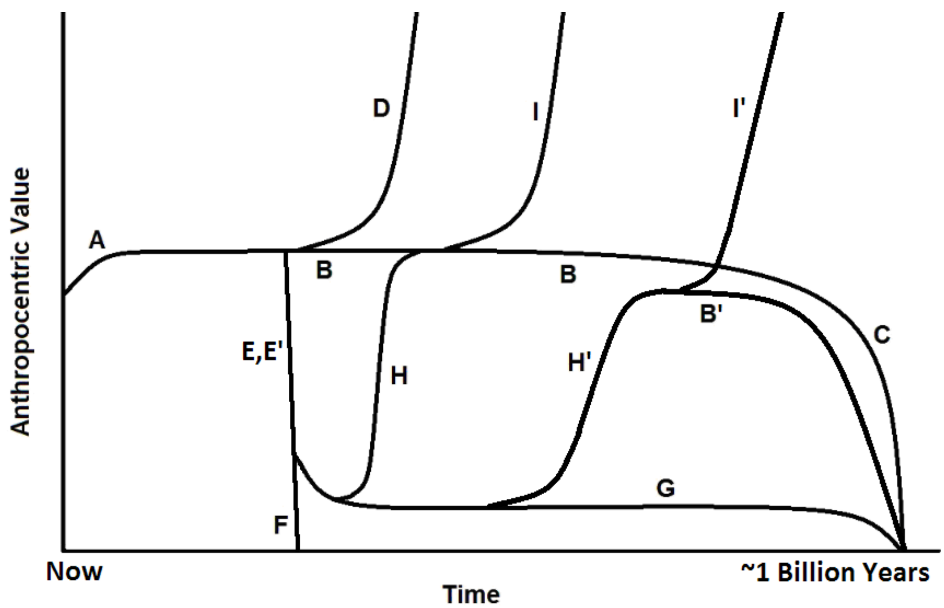
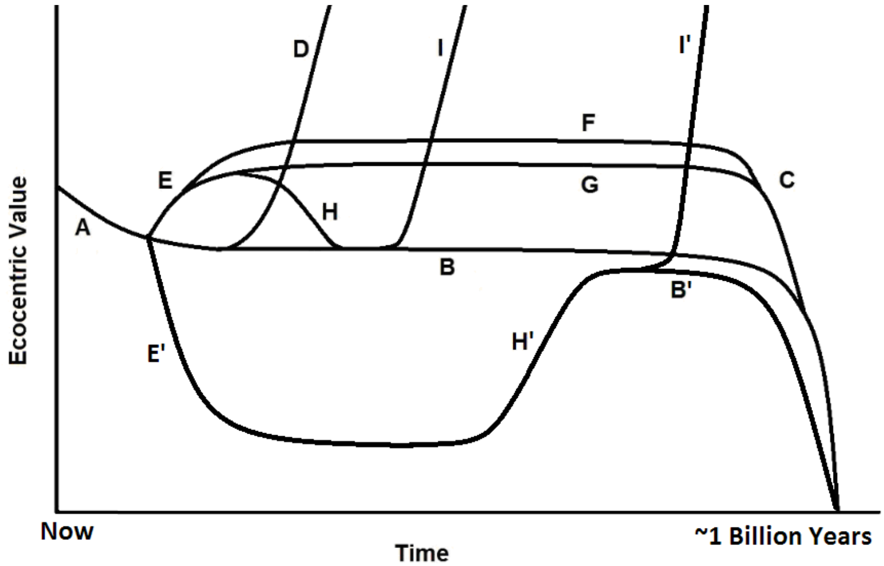


Figure 2. Rough sketches of several possible trajectories for human civilization, measured in ecocentric value. Curves are labeled alphabetically and are also not drawn to scale.



Curve A shows humanity in its current state. Human population and wellbeing are growing, driving an increasing anthropocentric value. Human civilization growth is meanwhile causing environmental destruction, resulting in decreasing ecocentric value. Curve B shows human civilization growth leveling off, with corresponding stabilization of both anthropocentric and ecocentric value. Curve C shows the Sun eventually changing and rendering Earth uninhabitable, causing both anthropocentric and ecocentric value to decline to zero, as life on Earth dies out. This trajectory is the story of "status quo" Earth-life with humanity never colonizing space or suffering a global catastrophe.

Curve D shows humanity avoiding global catastrophe and going on to colonize space. As Earth-life expands out into the Solar System and beyond, both anthropocentric value and ecocentric value increase to very high levels. Anthropocentric value increases, because the immensity of space provides humanity with substantially greater resources to draw from. Ecocentric value also increases, because of the expanded resource base and, potentially, terraforming. Even if space colonies are highly artificial and bear little resemblance to Earthly "nature", the human colonizers themselves presumably hold at least some ecocentric value, which can be enough to bring large increases in ecocentric value, though this point may be debatable per different views on environmental ethics. That said, as drawn here, Curve D is clearly the best-case scenario in terms of both anthropocentric and ecocentric value. Indeed, the goodness of Curve D cannot even be seen in Figures 1 and 2, both because the instantaneous value can get too high to show here and because it can stay high for long after the time of the graph ends.

Curves E and E' show two global catastrophes. Both catastrophes cause a large, abrupt decline in anthropocentric value. E does not substantially harm global ecosystems, as may be expected in, e.g., a human disease outbreak. Indeed, since the greatly diminished humanity is no longer causing enormous environmental destruction, the result is an increase in ecocentric value. E' causes major harm to global ecosystems, as may be expected in, e.g., catastrophic climate change. In either case, the decline could be caused by one big catastrophe or by a sequence or system of cascading catastrophes (on the latter, see [11,26,27]). Curve F shows humanity failing to adapt to the global catastrophe and going extinct, sending anthropocentric value to zero and, for catastrophe E, sending ecocentric value to its highest level possible without space colonization. Curve G shows humanity adapting to the global catastrophe, but failing to recover, with anthropocentric value remaining low, but not zero, and ecocentric value remaining high, but below what it would be with human extinction. Curves H and H' show humanity recovering from the global catastrophes of E and E'. H has anthropocentric and ecocentric value, both returning to levels comparable to where they would be without catastrophe (*i.e.*, Curve B). In H', human recovery only occurs as ecosystem recovery gradually takes place, on time scales that may be comparable to ecosystem recovery after previous major extinction events in Earth's history. The result is levels of anthropocentric and ecocentric value (B') lower than pre-catastrophe levels (B) due to permanent effects of the catastrophe and/or conditions changing with the warming/expanding Sun. Finally, Curves I and I' show humanity colonizing space after recovering from global catastrophe, resulting in increases in both anthropocentric and ecocentric value comparable to that of earlier space colonization (Curve D), albeit at a delay. To repeat from above, the exact details of these curves are just rough sketches of how anthropocentric and ecocentric value could unfold and should not be interpreted as being precise.

This exercise in analyzing trajectories of human civilization clarifies the importance of adaptation to and recovery from global catastrophe. Clearly this does not diminish the importance of preventing global catastrophe or, for that matter, of colonizing space. A complete understanding of how to achieve success for Earth-originating life requires all of these pieces. With that, we now turn to the details of how global catastrophe adaptation and recovery could proceed.

3. The Processes of Global Catastrophe Adaptation and Recovery

Let us begin by assuming that some sort of global catastrophe will occur and that it will affect humanity in a way comparable to Curve E of Figure 1, *i.e.*, a large, abrupt decline in anthropocentric value. This is to say that the catastrophe will be a major threat to the viability of global human civilization, but without immediately causing human extinction. There will be some survivors, perhaps many survivors. We make this assumption purely for the sake of discussion; we do not intend this as a prediction of any sort. And let us further assume that the scenario could then proceed in either of three ways, depending on the success of adaptation and recovery. If adaptation fails, then humanity will go extinct, as in Curve F of Figure 1. If adaptation succeeds, but recovery fails, then humanity will persist in a diminished state, as in Curve G of Figure 1. If recovery succeeds, then humanity will restore itself to something resembling its current state, as in Curve H of Figure 1. The resemblance would likely not be perfect: survivors would probably not rebuild civilization as if nothing ever happened. Either way, sustaining human civilization requires at least successful adaptation and may also require successful recovery, depending on what specifically needs to be sustained and what human civilization would be like without recovery.

In the most general terms, successful adaptation and recovery depends on two factors: the conditions that survivors face and the survivors' ability to make the most of these conditions. The conditions will vary depending on the nature of the global catastrophe. A nuclear war will leave behind radiation and atmospheric dust; a pandemic will leave behind a pathogen; an ecological collapse will leave behind altered ecosystems. Any of these scenarios could in turn result in the cessation of global trade, resource scarcities and a demoralized human spirit. However, as noted in the Introduction, the complex and unprecedented nature of these scenarios renders them difficult to characterize.

Successful adaptation to global catastrophe can be defined most simply in terms of basic human needs. As long as humans have enough in the way of food, water, shelter, protection from disease and injury and other essentials, survival will be possible. The result may not involve the excitement of advanced modern technological civilization, let alone the possibility of colonizing space, but at least the human species will live on. That is, at least it will live on until it is wiped out by the next global catastrophe, be it a changing Sun (as in Curve C of Figures 1 and 2) or something sooner. Indeed, given the long time until the changing Sun catastrophe, it is likely that human survivors would first face catastrophe from a supervolcano eruption or large asteroid impact, just as the dinosaurs probably did about 65 million years ago.

Some insight into the feasibility of post-global-catastrophe adaptation can be derived from the success of pre-modern humans. For most of its existence, the human species has survived without such modern comforts as electricity, industrial manufactured goods and motorized transportation, let alone popular recent items, like mobile internet access. So, it is definitely possible for humans to survive in a world in which these comforts of modernity are not available. However, it does not necessarily follow that humans would survive in a post-catastrophe world. There are at least two fundamental differences between pre-modern and post-catastrophe human life. One difference is environmental: the catastrophe event may leave behind environmental stressors, such as radiation from nuclear weapons. Another difference is social/cultural: post-catastrophe humans were not raised for survival in post-catastrophe conditions. Pre-modern humans never had to deal with post-catastrophe environmental stressors, and they were raised to survive in the environments they faced. Because of these differences, the viability of pre-modern humans does not guarantee the ability of modern humans to adapt to post-catastrophe worlds.

Contemporary rural humans, especially those in poorer countries, may be the most likely to successfully adapt to post-catastrophe conditions [28]. These people may face the least in the way of environmental stressors if they are, e.g., further away from the cities being bombed, though this depends heavily on the specifics of the catastrophe scenario. Either way, they are also more likely to be able to survive without the comforts of modernity, simply because, to at least a degree, they already have been doing so. A subsistence farmer is well-positioned to continue feeding herself even without global food supply chains. Indeed, subsistence farmers may be humanity's greatest asset in preserving its existence in the wake of global catastrophes. This point suggests that populations of subsistence farmers should be protected from assimilation into non-self-sufficient modernity.

Successful recovery from global catastrophe is harder to define than it is for adaptation. At the heart of the definition rests a profound question: what does it mean for human civilization to succeed? Is it measured in the size of its population or the happiness of its people? Is it in the advances of its technology or the sophistication of its culture? Does it lie in individual success or the success of the collective or perhaps even the success of non-human animals and ecosystems? Lengthy tomes can be written pondering these questions. While these discussions are important, we will streamline the debate by recalling the enormous opportunities to be found in space colonization. For most of these conceptions of human civilization success, more success can be found beyond Earth than on it, simply because the rest of the universe is much larger. So, we define successful recovery from global catastrophe to have happened when human civilization recovers a space travel program that has the potential to colonize space. Actually colonizing space is not necessary, because we wish to distinguish the process of recovery from the process of colonization: Curves H/H' and I/I' in Figure 1.

Insight from pre-modern humans is harder to obtain for recovery than it is for adaptation. For adaptation, it is relatively straightforward to see that pre-modern humans worldwide were able to survive for many generations. However, it is harder to see the conditions that lead pre-modern humans towards modernity—indeed, this has been the subject of heated debate [29,30]. At the heart of the debate is whether modern civilization was achieved mainly due to environmental factors (such as favorable climates and the availability of agriculturally productive crops and animals or to social factors (such as political and economic institutions and industrious cultures). How this debate is resolved could determine the relative importance of environmental and social factors for post-catastrophe recovery. However, as with adaptation, environmental and social conditions will be different for post-catastrophe survivors than they were for pre-modern humans.

It is not immediately clear which human groups would most successfully recover, given that they have successfully adapted. Today's rural poor may be the most likely to adapt, but they may be the least likely to recover, given that their lives are furthest removed from the sort of technological civilization necessary for space colonization. However, the survivors may have up to one billion or so years to recover and colonize space, a time scale vastly exceeding the time scales of human evolution, expansion across Earth and technological advancement. Anatomically modern humans evolved about 200,000 years ago and left Africa about 100,000 years ago. This suggests that any surviving humans would have plenty of time to recreate advanced civilization before the Sun renders Earth uninhabitable, regardless of who those survivors are. However, with only one prior case of human cultural evolution, it is difficult to say whether surviving humans tend to create advanced civilizations or if the current line of humans just got lucky.

It is likewise difficult to say which humans would be more likely to go on to recreate advanced civilization. A key question is whether environmental factors or social factors are more important. If environmental factors are more important, then advanced civilization would most likely be recreated by humans in favorable environments. In this case, the form of the global catastrophe could be crucial: a catastrophe involving substantial ecological degradation (E' in Figure 2) would make recovery much more difficult than a catastrophe involving ecological gains (E in Figure 2). However, if social factors are more important, then advanced civilization would most likely be recreated by humans with more favorable social attributes, and the form of the catastrophe would be less important. Knowing which factors are important could help with pre-catastrophe preparations aimed at facilitating recovery.

Thus far, this section has given a rough sketch of the global catastrophe adaptation and recovery processes. Much more can and should be said. While there has been little dedicated research on this topic, we do see opportunities to use other lines of research for this purpose. The study of adaptation to global catastrophe can benefit from studies of pre-modern humans and contemporary subsistence farming communities, as well as of adaptation to local catastrophe. The latter includes literatures on disasters and disaster recoveries [31], emergency management, social learning and related fields. The study of recovery from global catastrophe can benefit from studies of human cultural evolution and the emergence of modern technological civilization, including literatures on development, as well as studies of recovery after local catastrophe. Both adaptation and recovery could benefit from insights from the arts, including science fiction, which has perhaps invested more energy than any other field into imagining how humans could get by post-catastrophe [28]. Also, both adaptation and recovery could benefit from the literature on resilience, a rich concept with applications to many contexts.

4. Insights from the Resilience Literature

The concept of resilience has diverse roots from the fields of psychology [32], materials sciences [33], business and industry [34] and social ecology [35]. Within each field, the general concept of resilience refers to the ability of some object or system to withstand a shock or rapid change. This section largely focuses on research from social ecology. In the 1970s and 80s, C.S. Holling began to identify patterns of resilience within ecological systems in an attempt to model periods of change in these systems [36]. Holling [35] defines ecological resilience as a "measure of the persistence of a system and its ability to absorb change and disturbance" without shifting to a new regime or stable state. Holling [35] also describes the stability of a system as the ability of that system to return to some initial equilibrium after a disturbance. Over time, it became clear that this language could also be used to explain more complex relationships between human and ecological systems [37]. To date, many researchers have used these concepts of resilience and stability to help us understand how best to manage and govern complex human-nature systems [36,37].

In order to better explain how these systems change over time, Holling developed the adaptive cycle framework [38]. The adaptive cycle is a heuristic model that explains the process by which system behavior can change. This change occurs with four stages: (1) growth/exploitation (r phase), (2) conservation/consolidation (K phase), (3) collapse/release (Ω phase) and (4) reorganization (α phase). The adaptive cycle can describe systems of many scales, from the lifecycle of microscopic bacteria to human social systems. Indeed, merging complex social science information with studies of ecological systems is often necessary, due to the large interactions between humans and the natural world. Understanding patterns of resilience in social-ecological systems can allow us to better assess how a system can successfully transition from the **Ω** collapse phase (catastrophe) to the α reorganization phase (adaptation) and then to the r growth/exploitation phase (recovery).

Over time, the adaptive cycle framework has evolved to better assess issues surrounding global change. Gallopín [39] discusses the ways in which the intellectual traditions of social and natural science use social-ecological systems analysis and how this analysis could be more useful for understanding global change if only these intellectual traditions were all using similar definitions. Folke *et al.* [40] attempt to unify these definitions by building upon previous work by Holling and discussing the related concepts of resilience, adaptation and transformation. Folke *et al.* define resilience as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain the same function, structure and feedbacks and therefore identity." Adaptation here is defined as the ability of actors to respond to a changing system and proceed along the current trajectory—a different use of "adaptation" than is employed in this paper. In this context, adaptation is a part of resilience. Folke *et al.* define transformation as the shift to a new trajectory or state, altogether. Folke *et al.* recommend that society begin managing smaller scale social-ecological systems to increase the larger scale Earth System resilience and to consider the possibility of actively transforming social-ecological systems that reduce Earth System resilience. As we discuss below, this idea can guide efforts to help adaptation to and recovery from global catastrophe.

The adaptive cycle framework has already been applied at length to local catastrophes, including adaptation and recovery as defined in this paper [36,41–46]. Much of this research uses case studies of local communities to identify patterns of resilience that may allow some societies to adapt and persevere through catastrophes and eventually recover [16,17,36,37,41,43–50]. One general idea from this research is that environmental, political and socio-cultural resilience can limit the damage of a catastrophe and even assist a society during reconstruction. Recent research suggests that social resilience may be more influential than environmental resilience in determining the outcome of a collapse and recovery scenario; environmental conditions are more likely to serve as the catalyst or trigger for a collapse, but if societal resilience is strong enough then the society may still recover [16,17]. Also relevant is the concept that societal resilience largely depends upon an abundance of options, information and cultural solidarity. Likewise, if a society is to adapt and recover from a catastrophic collapse, it generally must either maintain or reconstruct social institutions and cultural cohesion after undergoing mass socio-economic, socio-political and socio-cultural transformation. This transformation could either be a product of the catastrophe itself or a societal response to the catastrophe. For example, in addition to subsistence crises, catastrophe survivors may endure transformative poverty, anarchy and the up-ending of social roles that could break down social institutions and cultural cohesion [16]. The threat of violent conflict looms particularly large as a source of disruption, though the literature on environmental conflict finds that violence is hardly inevitable after events of environmental degradation [51–53].

The importance of societal resilience suggests several options for global catastrophe adaptation and recovery. One basic threat to societal resilience is the radical change in environmental and social conditions brought by the catastrophe. The change in conditions can force people to survive and thrive in new and unfamiliar ways. To succeed in such changing conditions, innovation is essential. One option to promote innovation in post-catastrophe societies is to promote it in pre-catastrophe societies, with the expectation that the skills and cultures of innovation will persist through the catastrophe. Likewise, one way to promote innovation is to promote decentralization. This can be seen, for example, in the history of agriculture: decentralized Western Europe was much more successful at innovation under changing conditions than authoritarian Ancient Egypt and Mesopotamia [16].

Another threat to societal resilience is the emergence of new ideologies and corresponding loss of cultural cohesion that can follow catastrophes. Mass social transformation (such as that caused by catastrophes) can induce the emergence of new ideologies [16]. These new ideologies may not spread uniformly across a society, resulting in new ideological differences that make the society less cohesive and, thus, more prone to conflict/less prone to cooperation. Without cooperation, adaptation and recovery can be less successful. One option to promote cultural cohesion is to retain socio-cultural memory (language, writing, information) of pre-catastrophe civilization to reduce the onset of new ideologies. Another option is to strategically adopt new ideologies, especially those gaining in popularity.

A third threat to societal resilience is the breakdown of law and order, which often occurs after catastrophes. Without law and order, the recovery of civilization may be impossible, and adaptation may even fail as violence, mismanagement and disorder plague catastrophe survivors. One option to keep or restore law and order is to temporarily create military leadership with the support of whatever local elites may exist. Such military regimes appear to have increased societal resilience during periods of Ancient Egyptian catastrophe-recovery [16,17] and, likewise, could help for global catastrophe survivors. However, any plans for military regimes should not overlook their potential downsides in terms of loss of liberty, procedural injustice and abuse of power. Meanwhile, other social formations may also be able to maintain law and order for post-catastrophe survivors without the downsides of military regimes.

Access to capital resources, especially those that can be directly used or consumed by the local post-catastrophe community, will also provide individuals with increased resilience [26]. Technological, natural, social and human capital are all useful here. It is important to note that capital that is considered valuable to a global economy prior to a catastrophe may not be considered as valuable or useful post-catastrophe. For example, electronic equipment would be of little value if the catastrophe destroys electricity grids. Likewise, the capital that proves to be valuable after the catastrophe may hold limited value prior to the catastrophe occurring. For example, hand tools for growing food are of limited value as long as industrial agriculture persists.

Many studies of local communities can be relevant to contemporary decision-making about global catastrophe [16,17,36,38,43,44,54]. If a global catastrophe occurs, then national and international governance mechanisms may no longer function. Survivors may be concentrated in small, isolated communities that may or may not self-organize. What policies could be enacted today to increase the resilience of these small isolated communities? Efforts to improve the resilience of a society prior to global catastrophe can be highly valuable. Governments could begin stockpiling these isolated communities with capital that may be valuable in a post-catastrophe world, such as vitamins, medical equipment, fallout shelters, mass quantities of dry food stores, libraries of information and weapons. Governments could also develop programs to train representatives from isolated communities with skills that may be relevant to post-catastrophe scenarios. Possible relevant skills could include military training, survival skills, first aid, education on potential catastrophe events and subsequent environmental changes or engineering. Finally, in the event that these stockpiles and pre-survivor communities could be targets of terrorism or other anti-humanistic attack, protective measures could be taken, whether from governments, the communities themselves or other means.

A few studies have attempted to extend the local catastrophe and resilience research to include global threats. Pahl-Wostl [55] assesses the adaptive capacities of regional water management regimes to respond to changes in global water availability and quality, concluding that these regional regimes are largely too rigid and incapable of adapting to changing conditions. Pahl-Wostl [55] determines that a larger scale global water governance regime is needed to accurately address future issues of water distribution. Similarly relevant is work on global Earth system planetary boundaries, which analyzes the risk of unacceptable global environmental change occurring as Earth system resilience is exceeded [8]. Finally, Barnosky *et al.* [1] analyze possible transformative state shifts within the global ecosystem and attempt to understand the interactions between shifts on the local and global scales [1]. Barnosky *et al.* [1] conclude that current and future civilization is likely forcing a number of local transformations beyond a threshold that will induce massive global change within this century. This global transformation will subsequently impact local scale social-ecological systems, as well.

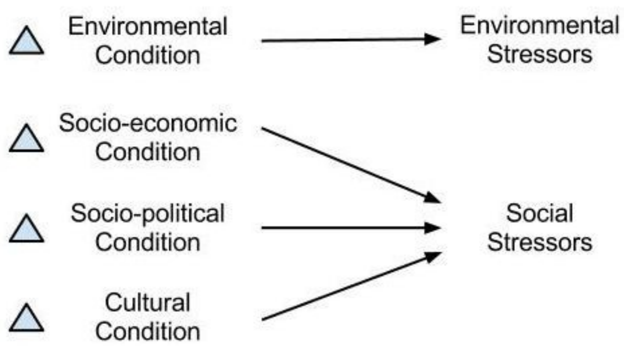
All this research suggests opportunities for resilience theory to make important contributions to the study of global catastrophe adaptation and recovery. We now present a resilience-based approach to analyzing global catastrophe adaptation and recovery, introducing the concepts of environmental and social stressors.

5. Environmental and Social Stressors

In this section, we present a method for research on global catastrophe adaptation and recovery. The method uses concepts from the adaptive cycle framework and systems theory, as well as analysis of historical periods of collapse, adaptation and recovery. The core of the method involves identifying post-catastrophe environmental and social stressors. Post-catastrophe survivors would be subject to a host of changes in their environment, inducing a new set of stressors under which survivors must attempt to thrive. A systems approach can help to assess survivors' potential vulnerability and resilience to these new stressors [56].

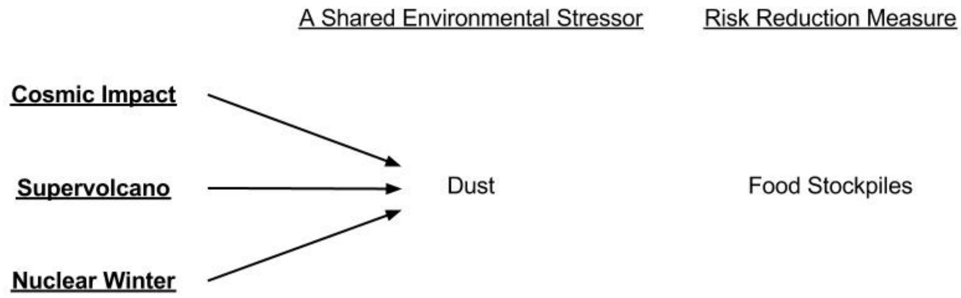
Survivors of a global catastrophe would face novel environmental and social conditions. These conditions may place stress on the survivors, as outlined in Figure 3. Note that Figure 3 is intended as an outline and not as a comprehensive diagram; in particular, it neglects the possibility of interactions between environmental and social conditions and stressors. These stressors are what survivors must adapt to and recover from, which is why the stressors are important to focus on. If the stressors are too large and the survivors cannot adapt, then their resilience will be exceeded, and they will die. If adaptation succeeds, the stressors may nonetheless prevent recovery (G in Figure 1). Thus, efforts to promote successful adaptation and recovery should concentrate on describing the stressors and how they may be overcome.

Figure 3. Outline of how changes in the environmental or social conditions lead to new environmental or social stressors on survivors.



Some stressors are unique to specific global catastrophe scenarios, whereas others are common to multiple scenarios. As a general trend, environmental stressors appear to depend more on the specifics of the catastrophe than is the case for social stressors. For example, only survivors of a nuclear winter will have to contend with increased exposure to radioactive isotopes; survivors of a pandemic or ecological collapse would not. In contrast, survivors of most global catastrophes will find themselves in a world without a global economy capable of providing specialized goods and services. However, there are exceptions. Survivors of cosmic impact (e.g., asteroids), supervolcano or nuclear winter would all face the environmental stressor of atmospheric dust (Figure 4). Also, only survivors of a pandemic would face the social stressors of isolation from infected individuals and fear of coming in contact with people who may be infected. Stressors common to multiple catastrophe scenarios are an advantage for purposes of increasing resilience, since the same resilience-increasing effort would help for each scenario.

Figure 4. The identification of one stressor shared among several catastrophe scenarios could efficiently result in a single risk reduction measure to be implemented in several catastrophe scenarios.



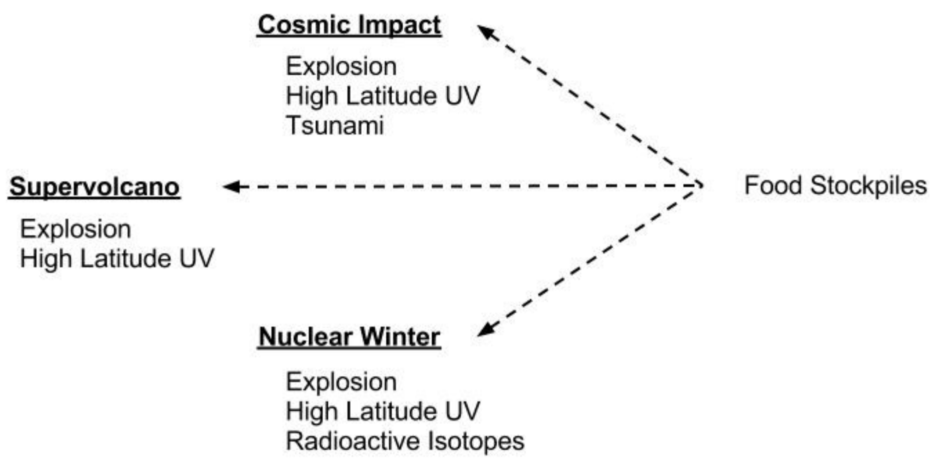
The usefulness of studying stressors can be seen via the environmental stressor of atmospheric dust (Figure 4). As noted above, the atmospheric dust stressor would affect survivors of a nuclear war [57], supervolcano eruption [13] or large cosmic impact event [58]. The stressor would result in reduced availability of solar radiation, reductions in global and regional temperatures and corresponding reductions in photosynthetic productivity. This dust could remain in the atmosphere for several years, potentially eliminating agricultural production throughout this period. If the dust is abundant enough, it may also deplete high-altitude ozone, which would result in increased exposure to ultraviolet (UV) radiation, especially at higher latitudes [59]. Increased UV exposure could further damage biological organisms, including humans and any remaining agricultural crops. All of these environmental stressors could make adaptation and recovery more difficult for survivors of nuclear war, a supervolcano eruption or a large cosmic impact event.

One way to increase resilience to the atmospheric dust particle stressor and, in turn, facilitate adaptation and recovery is creating and maintaining of strategically placed food stockpiles. Food stockpiles would help people survive the decline in agricultural production caused by the dust. The stockpiles could be strategically placed near those people most likely to survive the initial catastrophe, since in the absence of global shipping, food stockpiles in one region would not help people in another region. For example, communities near the equator may be more likely to survive, because the equator has higher solar radiation levels, higher ambient temperatures and reduced UV exposure. Placing food stockpiles at the equator may help communities there survive the initial catastrophe, adapt to the new conditions and eventually recover civilization. Such efforts could help maximize the overall likelihood of successful adaptation and recovery, as in Curves G and H of Figure 1, even if they would not help what survivors there were in other regions.

Effective implementation of food stockpiles could also depend on institutional considerations. For example, would it be acceptable for the different food stockpiles to be created and managed independently of one another? Or would implementation efforts be more efficient if operating under a single entity or umbrella institution? On one hand, coordinating efforts could help minimize these costs of implementation. On the other hand, global collaboration could impede projects by introducing excessive bureaucracy and could be less resilient to system-wide disruptions. Another institutional consideration concerns who sponsors the stockpiles. There may be a mismatch between those most able to sponsor the stockpiles (*i.e.*, the pre-catastrophe wealthy) and those most able to use the stockpiles (the pre-catastrophe rural poor). One option here is to sell access to the super-rich: in exchange for ongoing sponsorship of the stockpiles and the communities who maintain them, the sponsors would get preferential access if a catastrophe appears imminent, possibly helping the sponsors survive when few others would. This proposal is somewhat in the spirit of the refuge markets proposed by Hanson [60].

While the food stockpile measure is designed to help with the atmospheric dust stressor, it can also be affected by other stressors (Figure 5). The supervolcano, nuclear war and cosmic impact catastrophe scenarios all involve large releases of energy that could threaten the food stockpiles. For the food stockpiles to help survivors, they must either be designed to withstand the energy releases or be located sufficiently far from the energy releases. Additionally, each catastrophe would result in increased surface exposure to UV radiation, which could reduce the nutrient value and, thus, the usefulness of the food stockpiles. A nuclear winter would also result in the post-catastrophe environmental stressor of increased exposure to radioactive isotopes, which could result in food contamination. If a cosmic impact were to land in the ocean, it could induce a tsunami that could contaminate or otherwise destroy food stockpiles. Successful food stockpiles must endure these other stressors.

Figure 5. The chosen risk reduction measure must be resilient to other aspects of each catastrophe for which it may be used.



Synthesizing how all these stressors would affect food stockpiles suggests that stockpiles would be most effective if placed underground, at higher elevations and near the equator, *i.e.*, embedded within equatorial mountains. Prime candidates could include the equatorial Andes of South America, which contain many high-elevation cities, such as La Paz, Bolivia and Pasto, Colombia. Underground locations in this region would be sufficiently shielded from tsunamis, blast waves and exposure to UV radiation and radioactive isotopes. Stockpiles placed here are, thus, relatively likely to endure the initial catastrophe and be accessible to nearby survivor populations. In the event of a catastrophe, these stockpiles could help survivors remain alive long enough to adapt to the new conditions and recover civilization. However, we emphasize that the analysis and conclusions here are tentative. A more thorough analysis of food stockpiles should include other stressors, in particular social stressors.

As noted above, social stressors and resilience to these stressors can be at least as important as environmental stressors in determining the outcomes of human populations after catastrophes [16,17]. For example, in order for food stockpiles to help overcome the environmental stressor of atmospheric dust, the population near the stockpiles must organize itself in new ways to access and distribute the food. A key question is thus how the catastrophe would affect social institutions, such as governance structures and the rule of law. If social cohesion can be maintained, then the stockpiled food may be distributed in a fair and efficient manner. Without social cohesion, then the stockpiles could be a focus of looting, conflict and violence. In order for food stockpiles to successfully promote adaptation and recovery, there must be some means of overcoming these types of social stressors.

Meanwhile, there are other social stressors that cannot be resolved by food stockpiles alone. Many forms of global catastrophes—including cosmic impact, supervolcano and nuclear winter—induce major social transformations involving such stressors as breakdown of social institutions and loss of social memory—stressors identified as critical to adaptation and recovery [16,17]. Food stockpiles may be able to help keep people alive, but they cannot replace lost institutions and memories. One possible means of helping survivors overcome these social stressors is to ensure that they have access to large amounts of information, perhaps in the form of underground knowledge-banks, schools or libraries. These information hubs could offer training in relevant skill sets, knowledge to improve the persistence of social institutions and social memory and medical, engineering and other educational information to assist the reinstitution of technological advancement once survivors are capable of working towards such goals. In other words, such knowledge banks could provide vast amounts of social resilience to survivor communities.

Contingency plans like this (as in the case of the food stockpiling strategy) would require planners to address all of the challenges the post-catastrophe world would likely present. For example, would these libraries rely on electricity to power some database and interface tools? If so, planners must sufficiently plan for some form of long-term and independent power supply. If not, would the information be recorded on paper or other hardcopy material? If so, the tomes would need to be extremely large in order to incorporate all of the necessary information. It could be difficult to secure such large facilities from so many various catastrophe aspects and stressors. Finally, all this planning could be especially difficult if pre-catastrophe conditions are already deteriorating, as in the case of a gradually collapsing society.

Analyzing the intricacies of social stressors facing catastrophe survivors may ultimately be more complex than comparable research towards understanding the possible environmental stressors. However, research to reduce the risks from social stressors may be universally applicable to global catastrophe scenarios, which could result in greater efficiency of research efforts.

6. Conclusions

Global catastrophes threaten the long-term sustainability of human civilization. The stakes are astronomical, given that humanity could potentially colonize space and achieve results of great value across the universe. Most research on global catastrophes has focused on preventing the catastrophes from occurring. This research neglects the possibility that human survivors could adapt to post-catastrophe conditions, recover civilization and perhaps even go on to colonize space. To be sure, studying global catastrophe adaptation and recovery is a daunting challenge, given the complexity and unprecedented nature of the topic. Despite this challenge, we believe progress can be made.

This paper attempts to help fill this gap in the literature and make some progress by presenting discussion of why global catastrophe adaptation and recovery is important, how it could proceed and what humanity can do now to facilitate adaptation and recovery. Many lines of research can help account for the risks facing catastrophe survivors, including research on pre-modern humans, human cultural evolution, the emergence of modern technological civilization, contemporary subsistence farming communities, adaptation to and recovery from local catastrophe and socio-ecological resilience. These research areas can help describe the environmental and social conditions of post-catastrophe survivors. Changes in environmental and social conditions can lead to stressors that impede adaptation and recovery. In the extreme case, the stressors are too much for the survivors, exceeding their resilience and causing them to die.

To enhance the study of adaptation and recovery, we have developed a method for analyzing the environmental and social stressors associated with different global catastrophe scenarios. The method can help identify plans for promoting adaptation and recovery—plans that can be put in place now, before the onset of global catastrophe. An initial analysis of cosmic impact, supervolcano and nuclear winter scenarios suggests that food stockpiles could help overcome the environmental stressor of atmospheric dust. The stockpiles may be most effective if located in rural equatorial highlands, such as the equatorial Andes. An initial analysis of social stressors suggests that underground knowledge-banks, schools or libraries could help overcome the social stressors of breakdown of social institutions and loss of social memory—stressors associated with a broad range of global catastrophe scenarios.

The analysis in this paper only scratches the surface of the global catastrophe adaptation and recovery topic. Future work could include modeling exercises examining the consequences of various global catastrophes, including climate change, ocean acidification, nuclear war and global epidemics. Additionally, any efforts to increase our knowledge on social-ecological vulnerabilities and resilience would be useful. A productive approach would be applying the existing lines of research listed above to the topic of global catastrophe adaptation and recovery. In this paper, we have attempted to develop a starting point for such research.

Conflict of Interest

The authors declare no conflict of interest.

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