Global Catastrophic Risk Assessment

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About This Report

The world faces risks from many types of incidents consequential enough to significantly harm or set back human civilization at a global scale (i.e., global catastrophic risk) or even result in human extinction (i.e., existential risk). Given this possibility, in 2022, Congress passed the Global Catastrophic Risk Management Act (GCRMA).[1] The GCRMA requires the Secretary of Homeland Security and the administrator of the Federal Emergency Management Agency (FEMA) to coordinate an assessment of global catastrophic and existential risk in the next 30 years. The U.S. Department of Homeland Security (DHS) Science and Technology Directorate and FEMA requested the Homeland Security Operational Analysis Center's (HSOAC's) support to conduct such an assessment, with a focus on risk associated with artificial intelligence, asteroid and comet impacts, nuclear war, rapid and severe climate change, severe pandemics, and supervolcanoes. This report presents those assessments, as well as the implications of these assessments that risk managers should consider when developing strategies and plans to respond to these global catastrophic and existential risks. These analyses will be useful in informing FEMA's response to the GCRMA and should be of interest to risk management professionals across government.

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About the Homeland Security Operational Analysis Center

The Homeland Security Act of 2002 authorizes the Secretary of Homeland Security, acting through the Under Secretary for Science and Technology, to establish one or more federally funded research and development centers (FFRDCs) to provide independent analysis of homeland security issues.[2] RAND operates HSOAC as an FFRDC for DHS under contract 70RSAT22D00000001.

The HSOAC FFRDC provides the government with independent and objective analyses and advice in core areas important to the department in support of policy development, decisionmaking, alternative approaches, and new ideas on issues of significance. HSOAC also works with and supports other federal, state, local, tribal, and public- and private-sector organizations that make up the homeland security enterprise. HSOAC's research is undertaken by mutual consent with DHS and organized as a set of discrete tasks. This report presents the results of research and analysis conducted under task order 70RSAT23FR0000099, Global Catastrophic Risk Assessment. The results presented in this report do not necessarily reflect official DHS opinion or policy.

For more information on the RAND Homeland Security Operational Analysis Center, see www.rand.org/hsrd. For more information on this publication, see www.rand.org/t/RRA2981-1.

[1] Public Law 117-263, Section 2, Division G, Title LXXIII, Subtitle A.

[2] Public Law 107-296, Section 1; Title III; Section 305, Federally Funded Research and Development Centers; as codified at U.S. Code, Title 6; Section 185, Federally Funded Research and Development Centers.

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Summary

Global catastrophic and existential risks hold the potential to threaten human civilization. Addressing these risks is crucial for ensuring the long-term survival and flourishing of humanity. Motivated by the gravity of these risks, Congress passed the Global Catastrophic Risk Management Act in 2022, which requires the Secretary of Homeland Security and the administrator of the Federal Emergency Management Agency to coordinate an assessment of global catastrophic risk related to a set of threats and hazards.[1] The U.S. Department of Homeland Security Science and Technology Directorate and the Federal Emergency Management Agency requested the Homeland Security Operational Analysis Center's support in meeting this requirement. This report documents findings from our analysis.

This report summarizes what is known about the risks associated with six threats and hazards:

- the use and development of artificial intelligence (AI)
- asteroid and comet impacts
- sudden and severe changes to Earth's climate
- nuclear war
- severe pandemics, whether resulting from naturally occurring events or from synthetic biology
- supervolcanoes.

We developed risk summaries that cover the following aspects:

- where feasible, estimates of the likelihood and potential consequences of each threat or hazard
- factors causing the risk and associated uncertainties
- whether the risk is likely to change in the next decade.

Because the broader goal of the Global Catastrophic Risk Management Act is to reduce risk to human civilization, we identified known and potential mitigation strategies for the six threats and hazards and drew insights from the assessment relevant to managing the risks they pose to society.

Key Findings

Overall, global catastrophic risk has been increasing in recent years and appears likely to increase in the coming decade. Table S.1 summarizes key aspects of the six risk assessments undertaken in this report. For supervolcanoes and asteroid and comet strikes, risk should remain constant or reduce in the next decade. For the remaining threats and hazards, the risk appears to be increasing in the next decade because of current or expected human activities. For AI, the uncertainties are sufficiently large that it is difficult to determine the extent or magnitude of changes in risk with any confidence.

Four key factors govern the changes in risks from the threats and hazards covered in this report:

- the rate and nature of **technological change**
- the **maturity of global governance and coordination**
- failure to advance **human development**, thereby threatening societal stability
- **interactions** among the hazards themselves.

[1] Public Law 117-263, Section 2, Division G, Title LXXIII, Subtitle A.

TABLE S.1

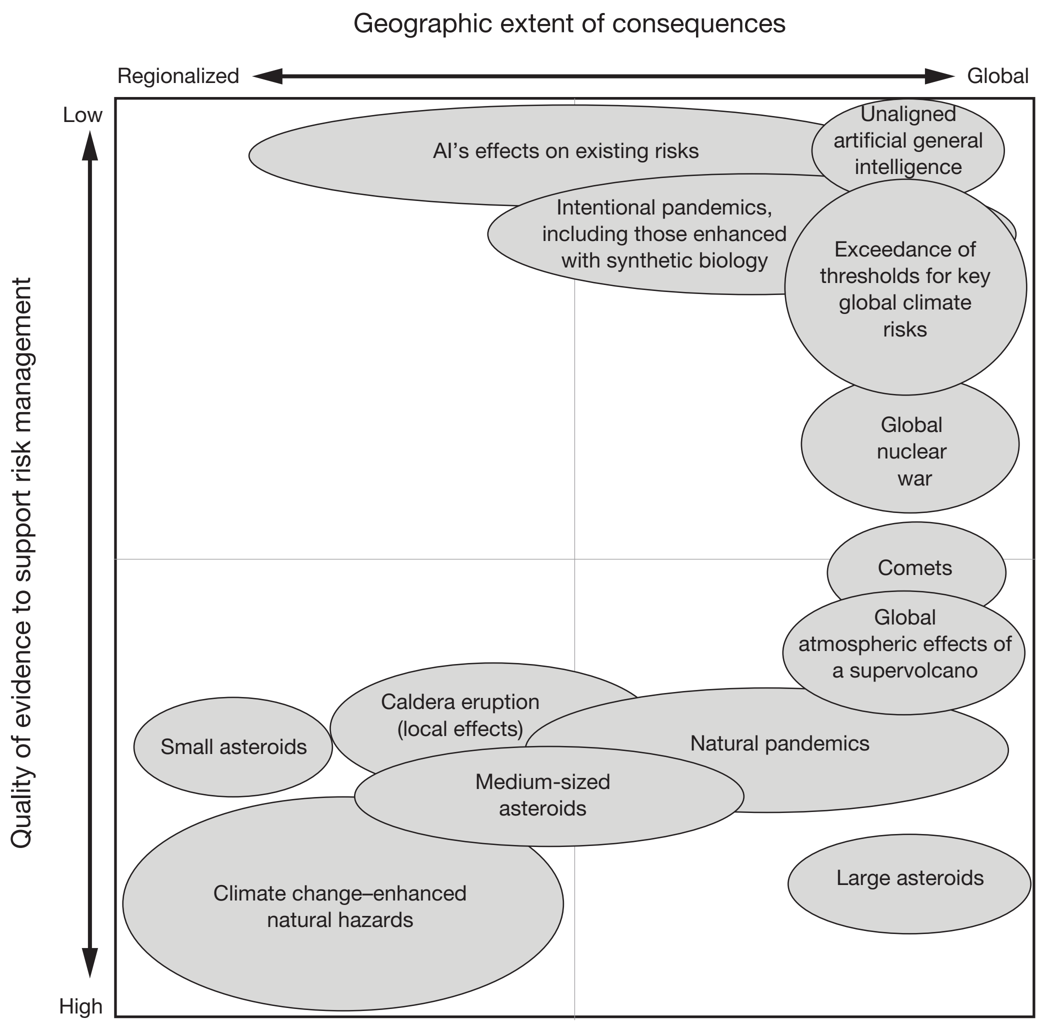
Summary Key Findings from the Risk Assessments

Hazard or Threat	Risk Dimension		
	Most-Significant Consequence	Likelihood of Risk	Quality of Evidence Supporting the Assessment
AI	• AI amplifies existing catastrophic risks, including risks from nuclear war, pandemics, and climate change. • AI systems have the potential to destabilize social, governance, economic, and critical infrastructure systems, as well as potentially result in human disempowerment.	• The likelihood of AI-enabled catastrophe is deeply uncertain and depends on human decisions about the safety and use of AI systems, as well as many other factors.	• Little empirical evidence exists for assessing the likelihood or consequence of AI risk, and little rigorous modeling exists to provide theoretical evidence.
Asteroid or comet impact	• Widespread physical destruction could have global range in the case of large impactors. • Large impactors could cause damage to the global ecosystem with the potential extinction of humans and many other species.	• Small impactors (~30 m diameter, city-sized devastation): every ~100 years • Medium impactors (~300 m diameter, country-sized devastation): every ~100,000 years • Large impactors (~3,000 m diameter, global devastation): every ~10 million years	• There is a geologic record of past major impacts and astronomical observations of near-Earth asteroids and comets.
Nuclear war	• Hundreds of millions of people could be killed directly, billions could be killed indirectly, and severe ecological damage could result in human extinction. • Destruction of economic value could total hundreds of trillions of dollars.	• Human decisionmakers influence the level of risk, so it can change rapidly. • Estimates that a nuclear war will occur during the 21st century vary from negligible to greater than 80%.	• The direct effects of nuclear weapons are well understood, while the indirect effects are less predictable but better studied than those of many other global catastrophic risks.
Climate change	• The primary significant consequences would be death, disruption, and degradation of ecosystem stability. • The secondary significant consequence would be the slowing of economic growth and reduced human capabilities induced by environmental, economic, and ecosystem damage.	• A 2.0°C rise in temperature is likely and considered catastrophic on a local to regional scale but not globally. The probability of more-severe global warming over 4.0°C is estimated to be less than 1% but could create potentially catastrophic outcomes.	• Observations of ecological changes and significant uncertainty about climate hazards and Earth-system tipping points exist, with robust near-term temperature predictions but greater uncertainty in later decades.
Pandemic	• The primary significant consequence would be mortality and morbidity associated with pandemics. • Secondary risks could result from “economic and social disruption on a massive scale” (White House, *National Biodefense Strategy and Implementation Plan*).	• Human behaviors increase the likelihood of a pandemic, but scientific discoveries and technology development increase humans’ understanding and capacity for managing pandemics, which could lower the severity of the risk.	• There is strong evidence that naturally occurring pandemics will increase, but little evidence exists for assessing the risk of a pandemic resulting from a laboratory accident or a deliberately engineered pathogen.
Super-volcano	• The primary significant consequence would be damage to the natural environment and ecosystem stability. • Secondary significant consequences would be societal instability, death, and reduced human capabilities induced by environmental and ecosystem damage.	• Annual exceedance probability of a supereruption (volcano explosivity index [VEI] 8) is 6.7×10^{-5}, which represents an approximate return period of 15,000 years.	• There is clear scientific evidence that supereruptions occur and an understanding about their regional effects when they do. However, the understanding of when and where they will occur and their global effects has limits caused by incompleteness of geologic records, modeling uncertainties, and inadequate monitoring.

The hazards and threats reviewed in this report can vary widely in terms of the geographic extent over which one can expect consequences to occur and the quality of understanding about their scope, likelihood, and consequences (see Figure S.1).

Generally, risk management practices needed to address the sorts of risks covered in this report fall into one of two broad categories: (1) actions to prevent the occurrence of the hazard or threat and (2) actions to reduce the consequences of the event. In the assessments presented in this report, we identified many current or potential steps that can be considered to reduce the risk of global catastrophe or human extinction, reduce uncertainty about these risks, or create new ways to mitigate them (see Table S.2). These include implementing technical or logistical solutions, improving governance and policy, and conducting research and development. In line with these categorizations of mitigation options and using the two dimensions of Figure S.1—the geographic extent of consequences and quality of evidence about the risks—the

FIGURE S.1
Quality of Evidence Supporting Risk Management and the Geographic Extent of Global Catastrophic and Existential Risks



NOTE: Placement and size of the ovals in this figure represent a qualitative depiction of the relative relationships among threats and hazards based on interpretation of aspects of the assessments described in Chapters 4 through 9. The figure presents only examples of cases or scenarios described in those chapters, not all scenarios described.

TABLE S.2

Hazard Mitigation Approaches, by Mitigation Dimension and by Hazard or Threat

Mitigation Dimension	Hazard Mitigation Approach					
	AI	Asteroid or Comet Impact	Nuclear War	Climate Change	Severe Pandemic	Supervolcanoes
Reduce the likelihood of occurrence.	• Develop safe, secure, and trustworthy AI systems. • Pause AI development until safety protocols are established.	• Try one or more experimental approaches of in-space deflection or disruption of threatening objects enabled by early detection of impactors.	• Reduce international tensions; reduce the number and power of nuclear weapons.	• Exercise one or more of the extensive technological, regulatory, and behavioral options to monitor and slow the accumulation of greenhouse gases in the atmosphere.	• Reduce human activities that contribute to naturally occurring, accidentally laboratory-induced, or deliberately caused pandemics, and reduce susceptibility through vaccination against the likeliest threats.	• Highly speculative options have been proposed, but no credible options are known.
Disrupt the mechanisms leading to risk.	• Oversee AI to determine risk for specific contexts. • Continue human oversight of AI decisions in high-risk domains. • Engage in postdeployment performance monitoring. • Retain the ability to modify or roll back AI systems in case of adverse outcomes.	• Try one or more experimental approaches of in-space deflection or disruption of threatening objects enabled by early detection of impactors.	• Engage counterforce for damage limitation and use active (air and missile) defenses.	• Exercise one or more experimental geoengineering options to offset radiative forcing and remove or sequester carbon dioxide.	• Reduce pandemic risk by addressing habitat encroachment, unsafe lab experiments, and misuse of technology.	• Highly speculative options have been proposed, but no credible options are known.
Reduce the severity of effects.		• Try one or more experimental approaches of in-space disruption of impactors, large-scale evacuations, timely public warning, and increasing human civilization’s resilience.	• Engage in civil defense (e.g., bomb shelters, evacuation, dispersal of potential targets).	• Exercise one or more of the extensive technological, regulatory, and behavioral options to avoid, reduce, or spread the risks that climate change poses to society; their deployment capacity varies.	• Develop pandemic preparedness measures and increase confidence in government institutions responsible for pandemic planning and response.	• Issue warnings and conduct large-scale evacuations. • Exercise one or more theoretical, untested geoengineering options, such as containing erupted material with stratospheric tents or sky bots and injecting greenhouse agents into the stratosphere.
Enhance response and recovery.	• This is not applicable, given the uncertainty about potential pathways and outcomes.	• Coordinate planetary defense efforts. • Prepare terrestrial responses (e.g., evacuations). • Increase human civilization’s resilience.	• Stockpile food and medical supplies; make continuity-of-government arrangements.	• Scale up existing response and recovery options to mitigate societal risks.	• Shorten timelines for development of medical countermeasures. • Improve strategic communications.	• Provide for disaster recovery, population evacuations, and developing replacement resources to sustain populations. • Coordinate and communicate observations and warnings.

results of this risk assessment reveal steps the U.S. government and other countries can take to reduce risks of global catastrophe and human extinction.

Recommendations

The United States and other countries should

- incorporate comprehensive risk assessments into management of global catastrophic and existential risks
- develop a coordinated and expanded federally funded research agenda to reduce the uncertainty about global catastrophic and existential risks and to improve the capabilities for managing such risks
- develop plans and strategies when global catastrophic and existential risk assessments are supported with adequate evidence
- expand international dialogue and collaboration on addressing global catastrophic and existential risks
- adapt planning and strategy development to address irresolvable uncertainties about global catastrophic and existential risks.

These actions should be viewed as preludes to an ongoing quest to understand and manage risks that can threaten humanity. Building and sustaining a resilient world will require continually identifying, assessing, managing, and monitoring the sorts of risks discussed in this report and other risks that might be lurking in the shadows of society's collective ignorance.

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CHAPTER 1

Introduction

The world faces risks from many types of incidents consequential enough to significantly harm or set back human civilization on a global scale (i.e., catastrophic risk) or even result in human extinction (i.e., existential risk). These risks are associated with both natural hazards and threats deriving from human-created inventions and actions. In 2022, Congress passed the Global Catastrophic Risk Management Act (GCRMA) with the goal of providing a comprehensive assessment of such risks for policymakers, emergency management planners, and other stakeholders.[1]

The GCRMA requires the Secretary of Homeland Security and the Administrator of the Federal Emergency Management Agency (FEMA) to coordinate an assessment of global catastrophic risk related to various threats and hazards and supplement each federal interagency operational plan with a strategy to ensure the health, safety, and general welfare of the civilian population affected by catastrophic incidents.[2] The legislation also calls for the U.S. Department of Homeland Security (DHS) and FEMA in particular to lead an exercise as part of the national exercise program to test and enhance the operationalization of the strategy and develop and update the strategy based on lessons from the exercise.

Scope of the Study

The DHS Science and Technology Directorate and FEMA requested support from the Homeland Security Operational Analysis Center to meet the initial requirements of the GCRMA related to assessing global catastrophic risk. These analyses serve as the foundation for fulfilling the other requirements of the act intended to reduce the risks from global catastrophic and existential risks. To provide the input requested by FEMA, we undertook the following activities called for by the GCRMA, which we describe in this report:

- Identify catastrophic or existential scenarios associated with the assessed threats and hazards, including those that might have very low likelihoods of occurring.
- Where reasonably feasible and credible, develop estimates for the likelihood of occurrence and potential consequences of each assessed threat and hazard.
- Describe factors affecting the likelihood of each threat or hazard occurring and its potential consequences.
- Describe factors that limit assessments of catastrophic and existential risk, both cumulatively and for particular threats, and how those limitations could be overcome through future research.

[1] Public Law 117-263, Section 2, Division G, Title LXXIII, Subtitle A.

[2] Federal interagency operational plans contribute to alignment of the federal government for implementation of national planning frameworks. These plans include incident annexes that address unique aspects of planning for specific threats and hazards that require considerations not addressed in the core plans. More information on these plans can be found at FEMA, "Federal Interagency Operational Plans."

- Describe whether and why global catastrophic and existential risk is likely to increase or decrease significantly in the next decade, both qualitatively and quantitatively, as well as a description of associated uncertainties.
- Discuss the implications of the risk assessments for how the federal government could more adequately assess and manage global catastrophic and existential risk on an ongoing basis in future years.

This report focuses on the following threats and hazards identified in the GCRMA, as defined in Box 1.1:

- intentional or accidental threats arising from the use and development of artificial intelligence (AI)[3]
- asteroid and comet impacts
- nuclear war
- rapid and severe changes to Earth's climate
- severe pandemics resulting from naturally occurring events and synthetic biology
- supervolcanoes.

Methods

To develop the risk assessments, we reviewed and synthesized unclassified, nonsensitive literature on assessments of the six threats and hazards covered in this study. We identified literature through structured keyword searches of research and scientific databases cataloging peer-reviewed, government, and private research papers and studies. Further details of the literature search methodology are provided in Appendix A. We limited the literature reviewed for this report to the scope of threats and hazards covered and the risk assessment frameworks described in Chapters 2 and 3. The findings provide a summary and analysis of the cited literature to support further risk analysis, research, and risk management planning of the threats and hazards identified in the GCRMA.

Organization of the Report

To help ground our analyses, Chapter 2 describes concepts related to global catastrophic and existential risk. Chapter 3 presents an overview of risk assessment and management frameworks that motivate how our team evaluated risk from the six natural hazards and human-caused threats identified in the GCRMA. Chapters 4 through 9, respectively, offer summaries of risk estimated for the six relevant threats and hazards, including high-level overview tables and discussions of underlying causes of risk from the threat or hazard; risk itself as a combination of likelihood and consequences; and potential risk mitigation opportunities. Chapter 10 is an integrative chapter that draws from insights across the threat- and hazard-specific chapters to inform planning and provides recommendations for policymakers on steps they can take to address the global catastrophic and existential risks presented by these threats and hazards. We have also provided three appendixes: Appendix A details our literature search, including the specific databases searched and all our search queries, Appendix B provides additional information on terms that might be unfamiliar to the lay reader, and Appendix C lists all works cited, by chapter.

[3] The GCRMA specifically identifies risks stemming from the "use and development of emerging technologies." This assessment focuses on the development of AI and advances in synthetic biology. We describe risks from synthetic biology advances in the context of risks from severe pandemics.

BOX 1.1

Definitions of Threats and Hazards Assessed in This Report

- **AI:** For the purposes of this work, *AI* refers to computer systems that can perform tasks at or approaching the level of human capability, such as visual perception, speech recognition, problem-solving, decisionmaking, and learning. As AI systems become more capable, as people place these systems in positions of increasing influence and control, and as competition drives developers and adopters to rush development and use, many people are concerned about the intentional or accidental consequences of their deployment.
- **Asteroid and comet impacts:** The intersection of large asteroids' or comets' orbital paths with Earth's orbit creates the potential for a collision that can cause a blast wave, thermal pulse, ejecta, and other devastating effects.
- Rapid and severe **climate change**: Human-induced changes in the climate system, largely associated with past and future emissions of greenhouse gases (GHGs), will have significant adverse effects on the global environment and, by extension, human well-being. Climate change–related disruptions to the natural environment have implications for weather patterns, sea levels, food and water security, and infrastructure, thereby posing a risk to human health, the economy, and national security.
- **Nuclear war:** Nuclear weapons harness the energy of nuclear fission and fusion reactions to produce extremely powerful explosions (e.g., equivalent to the detonation of tens of thousands of tons of trinitrotoluene [TNT]). Such explosions produce both prompt and delayed effects that can harm individual humans, essential infrastructure, and large-scale ecosystems. Since the first use of nuclear weapons in 1945, many people have perceived large-scale use of these weapons in war as a key global catastrophic risk that could imperil the viability of human civilization.
- **Pandemics:** A pandemic is a "disease outbreak that spans several countries and affects a large number of people."[a] The designation of a public health event as a pandemic relates to the severity and spread of the disease over a wide area. Pandemics can be triggered by naturally occurring events or initiated accidentally or with use of a pathogen that has been engineered using synthetic biology.
- **Supervolcanoes:** Supervolcanoes are volcanoes that produce extremely large, violently explosive eruptions on a scale never experienced by modern humans. Depending on where they are, supervolcano eruptions could cause great damage from both the pyroclastic flow and ash plume that are injected into the atmosphere and dispersed up to thousands of meters away from the eruption site and from emissions of sulfur gases that are injected into the atmosphere and could have a catastrophic effect on Earth's climate.

[a] DHS, "Pandemics."

CHAPTER 2

What Are Catastrophic Risk and Existential Risk?

The GCRMA defines *global catastrophic risk* as "the risk of events or incidents consequential enough to significantly harm or set back human civilization at the global scale."[1] It defines *existential risk* as "the potential for an outcome that would result in human extinction."[2]

This chapter elucidates these definitions of global catastrophic and existential risk and situates them within a broader set of perspectives. The chapter also highlights several important considerations about the analysis of global catastrophic and existential risks, including factors influencing how people perceive them and differing ethical perspectives on their policy importance. The goal of the chapter is to establish how we interpret the GCRMA definitions and to support a broad approach to risk assessment, discussed in Chapter 3, that accommodates these complexities.

Accounts of Existential Risks

Discussions of catastrophe are not new, and thinkers across cultures have considered these possibilities. For example, in Hindu sacred texts, the universe proceeds through cycles of creation and destruction as expressed through deities, such as Brahma (the creator), Vishnu (the preserver), and Shiva (the destroyer).[3] According to Yoruba beliefs, the supreme deity periodically withdraws the energy that sustains the world, eliminating all life in a cleansing process that allows regeneration.[4] And many cultures have stories about world-destroying floods, including Noah's Ark in the Torah and the Old Testament, the Mesopotamian floods as told in *The Epic of Gilgamesh*, and Nuwa's role in saving humans from a devastating deluge as detailed in ancient Chinese texts.[5]

The prevalence of these accounts suggests something universal and meaningful about thinking of catastrophe. Many of these accounts feature the destruction of the world but also some return or continuation of humanity. However, *existential* risk involves a type of permanent, unrecoverable end of human potential.

Academic Accounts

In a discussion that initiated increased academic research on existential risk, philosopher Nick Bostrom laid out a taxonomy of risk based on the scope (or size) of the group of people affected and the intensity of

1 U.S. Code, Title 6; Section 821(6), Global Catastrophic Risk.

2 U.S. Code, Title 6; Section 821(5), Existential Risk.

3 Shastri and Tagare, *Ancient Indian Tradition and Mythology*; *The Siva-Purana*; Wilson, *Vishnu Purana*.

4 Karade, *The Handbook of Yoruba Religious Concepts*.

5 *The Epic of Gilgamesh*; *The Classic of Mountains and Seas*.

the outcome.[6] He defined *existential risk* as "one where an adverse outcome would either annihilate Earth-originating intelligent life or permanently and drastically curtail its potential."[7]

Bostrom distinguished these existential risks from adverse outcomes that are global in scope and affect all people but are of endurable intensity and thereby allow the continued realization of the potential of human civilization (his example is the thinning of the ozone layer). He also distinguished existential risks from terminal risks that are localized in scope (his example is a genocide of a specific culture or people). Bostrom's existential risks are those that terminate all human potential, although this does not exclusively mean human extinction.[8] Bostrom discussed nonextinction events that he wrote would drastically curtail humans' potential, such as through a misguided world government or a "badly programmed" artificial superintelligence.[9]

Policy Institution Accounts

In addition to academics, public policy organizations worldwide have recently engaged with existential risk. For the first time since the National Intelligence Council began publishing Global Trends reports in the late 1990s, the 2021 Global Trends 2040 report described the concept, noting that "threats that could damage life on a global scale challenge our ability to imagine and comprehend their potential scope and scale."[10] The National Intelligence Council report further notes that these risks are "low-probability, high-impact events [that] are difficult to forecast and expensive to prepare for" and that "technology plays a role in both generating these existential risks and in mitigating them."[11]

The United Nations Office for Disaster Risk Reduction's account of existential risk emphasizes both human extinction and permanent curtailment of human development, including in its definition events "leading to either human extinction or the irreversible end of development."[12]

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6 Bostrom, "Existential Risks." Some people have credited Bostrom, the founding director of the Future of Humanity Institute at the University of Oxford, with initiating an entire research field on existential risk known as *existential risk studies* (e.g., in Torres, *Human Extinction*). Many other 20th-century thinkers preceded Bostrom, and some noteworthy works include Meadows, Randers, and Meadows, *Limits to Growth*; Sagan, "Nuclear War and Climatic Catastrophe"; and Schell, *The Fate of the Earth*.

7 Bostrom, "Existential Risks."

8 See "Differing Interpretations of Human Extinction" later in this chapter. One might not know in advance whether a collapse would involve a permanent or unrecoverable harm or whether eventually humans might recover.

9 Others, such as Toby Ord in *The Precipice*, have followed Bostrom's definition. According to Ord, existential risks are "risks that threaten the destruction of humanity's long-term potential" (p. 37). Like Bostrom's definition, this includes extinction but also other dystopian possibilities that involve an unrecoverable curtailing of human civilization. These scenarios of "failed continuation" of human life could result from an unrecoverable catastrophe (for example, if Earth's environment "was damaged so severely that is has become impossible for the survivors to re-establish civilization" [p. 36]) or in an unrecoverable dystopia (for example, if the "entire world has become locked under the rule of an oppressive totalitarian regime" [p. 36]) (Ord, *The Precipice*).

10 National Intelligence Council, *Global Trends 2040*, p. 65.

11 National Intelligence Council, *Global Trends 2040*, p. 65. Other U.S. government entities have discussed existential risk; for instance, Secretary of Defense Lloyd Austin has called climate change an existential risk; see Vergun, "Defense Secretary Calls Climate Change an Existential Threat."

12 Stauffer et al., *Existential Risk and Rapid Technological Change*, p. 4.

Differing Interpretations of Human Extinction

The GCRMA defines *existential risk* with a focus on human extinction: "[T]he term 'existential risk' means the potential for an outcome that would result in human extinction."[13] It is worth noting that human extinction is itself a complex concept with differing interpretations about what constitutes humanity and what it would mean for humans to be extinct. By some accounts, extinction would occur only if the human population were to reach zero. However, some research defines *human extinction* as occurring when the human population falls under certain thresholds, such as reducing the number to less than 5,000.[14]

There are also debates about what constitutes humanity and its relationship to human life and culture. In some theories, humanity might continue, even if it is radically reshaped. For example, humanity might continue even if people are forced to live entirely underground or on another planet, if they no longer have free will because of some powerful manipulative force, or if they upload their minds to a digital computer and transition into some type of posthuman or transhuman life.[15] Insofar as these future beings have some causal or genealogical connection to today's humans, some might think that their existence constitutes humanity's continuation. However, others might deem those outcomes to be the end of humanity, in which human continuity would require the preservation of the planet on which humans have evolved; the agency to undertake meaningful activities; or a type of organic, embodied experience of *Homo sapiens* participating in a recognizable human culture.[16]

To accommodate these theoretical complexities, we interpret *existential risk* and related concepts of global catastrophe to involve consequence categories beyond the number of fatalities, such as the broader notions of well-being and institutional stability. We further discuss these consequence categories in Chapter 3.

Global Catastrophic Risk

Global Catastrophic Risk in the Global Catastrophic Risk Management Act

Global catastrophic risk—a term related to but broader than *existential risk*—is a primary focus of this report. This type of risk might not involve human extinction or other unrecoverable outcomes, but the GCRMA envisions other types of severe consequences that harm humans and overwhelm institutions.

The GCRMA defines *global catastrophic risk* as "the risk of events or incidents consequential enough to significantly harm or set back human civilization at the global scale."[17] This setback of global civilization is further explained in other parts of the GCRMA; for instance, in the language of the legislation, *catastrophic incident*

> (A) means any natural or man-made disaster that results in extraordinary levels of casualties or damage, mass evacuations, or disruption severely affecting the population, infrastructure, environment, economy, national morale, or government functions in an area; and (B) may include an incident—(i) with a sustained national impact over a prolonged period; (ii) that may rapidly exceed resources available to State and local government and private sector authorities in the impacted area; or (iii) that may significantly

[13] U.S. Code, Title 6; Section 821(5), Existential Risk.

[14] Karger et al., *Forecasting Existential Risks*.

[15] There are a variety of philosophical accounts of post and transhumanism that we do not discuss here. Some key texts include Bostrom, "What Is Transhumanism?" and essays in the collected volume More and Vita-More, *The Transhumanist Reader*.

[16] Torres, *Human Extinction*, offers a detailed discussion of different concepts of extinction.

[17] U.S. Code, Title 6; Section 821(6), Global Catastrophic Risk.

> interrupt governmental operations and emergency services to such an extent that national security could be threatened.[18]

In addition, the GCRMA defines *global catastrophic and existential threats* as "threats that with varying likelihood may produce consequences severe enough to result in systemic failure or destruction of critical infrastructure or significant harm to human civilization."[19] In these definitions, the GCRMA points to some of the consequences associated with global catastrophic risk, such as extraordinary numbers of casualties, disruption of government capabilities, negative economic effects, and harms to the environment and social morale.

The Role of Civilization Collapse

The GCRMA definition of *global catastrophic risks* is risks that "significantly harm or set back human civilization at the global scale."[20] This reference underscores an essential element of catastrophic risk to which we refer as *civilization collapse*.

Although the definition of *civilization collapse* is contested, we take it to mean a relatively rapid process of social and political disaggregation that results in a significant loss of societal stability, generally accompanied by large-scale death, economic decline, and government disintegration.[21]

A civilization collapse could result in a permanent loss of human potential or a descent into extinction—perhaps because it denies humans the ability to mitigate risks (e.g., asteroid impacts), or perhaps the process of collapse leaves the survivors in possession of instruments of destruction (e.g., nuclear materials or pathogens).[22] It thus appears useful to consider the potential for civilization collapse both as a result of global catastrophic risk and as a pathway to existential risk, as is done in this report's upcoming chapters.[23]

Other analysis of civilization collapse has considered the ways in which catastrophes might result in collapse and possibly also extinction over different temporal trajectories, such as through the demise of agriculture and industry.[24] For the purposes of this report, we note that different types of risk might incur consequences in different time frames; although an asteroid impact might rapidly lead to catastrophe, the continued integration of AI into critical infrastructure might lead to civilization collapse through lengthy processes with slower-accumulating harms (i.e., the proverbial frog slowly cooked in the pot). We interpret the category of global catastrophic risk to also include these slower forms of widespread global harm.

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[18] U.S. Code, Title 6; Section 821(3)(A), Catastrophic Incident.

[19] U.S. Code, Title 6; Section 821(7), Global Catastrophic and Existential Threats.

[20] Public Law 117-263, Section 2, Division G, Title LXXIII, Subtitle A.

[21] Belfield, "Collapse, Recovery, and Existential Risk." See also Steel, DesRoches, and Mintz-Woo, "Climate Change and the Threat to Civilization," which describes civilization collapse as

> the loss of societal capacity to maintain essential governance functions, especially maintaining security, the rule of law, and the provision of basic necessities such as food and water. Civilization collapses in this sense could be associated with civil strife, violence, and widespread scarcity, and thus have extremely adverse effects on human welfare. (p. 2 of 4)

[22] It is even possible that there was a prior civilization on Earth that was completely destroyed, with no evidence of that civilization left because of geological and other processes. For discussion, see Schmidt and Frank, "The Silurian Hypothesis."

[23] The processes by which civilization might (or might not) recover from a collapse are poorly understood. Nonetheless, some scholars have argued that humans could recover from a civilization collapse (Bostrom, "Existential Risks"; Ord, *The Precipice*); indeed, many historical and religious accounts of catastrophe have envisioned such a recovery.

[24] Baum et al., "Long-Term Trajectories of Human Civilization."

Alternative Accounts of Global Catastrophic Risk

A comparison to alternative definitions of global catastrophic risk further helps elucidate the GCRMA's definition. A paper submitted to the United Nations Office for Disaster Risk Reduction distinguishes global catastrophic risk from existential risk and adapts a definition that concretely identifies global catastrophic risks as follows:

> those that result in over 10 million fatalities, or greater than $10 trillion in damages [sic], essentially the damage must be extensive and on a global scale . . . . They are global in nature, but there is the expectation that humanity can recover for [sic] them as opposed to Existential Risk . . . events that are extinction events for humanity, and are a subset of GCR [global catastrophic risk] events . . . .[25]

By this threshold, global catastrophes have already taken place throughout history, including during the 1918–1920 influenza pandemic, multiple wars and famines, and totalitarian governments.[26] Some existing phenomena might also reach this threshold—for instance, there are approximately 10 million fatalities per year from cancer and more than 20 million fatalities per year from cardiovascular disease.[27]

Given that this definition of *global catastrophic risk* does not seem to cover cancer, heart disease, or other ongoing, existing causes of death, the definition seems to envision a novel or exogenous event that comes with a sudden or immediate onset. In addition, despite the terribleness of these ongoing events, civilization has nonetheless persisted in the face of them. Exclusion of these events supports an understanding of global catastrophic risks that involves novel events that might result in civilization collapse.

That said, the exclusion of existing processes that result in significant fatalities might have implications for which types of hazards are prioritized in public policy. As Bostrom and Ćirković put it, "It would be perverse if the study of possible catastrophes that *could* occur were to drain attention away from actual catastrophes that *are* occurring."[28] We further discuss these potential trade-offs in "Ethical Perspectives on Global Catastrophic Risk" later in this chapter.

The "10 million fatalities or $10 trillion in damages [sic]" threshold definition of *global catastrophic risk* also seems to preclude slow-onset or gradual processes that might result in significant harm over time, such as the ongoing environmental and social harms from climate change. We note also that this threshold references only fatalities or economic harm and thus might not include other extremely detrimental effects from catastrophic incidents, such as diminishments to government stability or broader quality of life, that we include as consequence categories in our risk assessment framework. The risk framework in Chapter 3 thus employs this threshold definition along with other measures of catastrophic risk.[29]

Related Risk Concepts

The debate over catastrophic and existential risk intersects with several related risk concepts.

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[25] Cernev, *Global Catastrophic Risk and Planetary Boundaries*, p. 6. See also Bostrom and Ćirković, *Global Catastrophic Risks*.

[26] Bostrom and Ćirković, *Global Catastrophic Risks*, lists these and other events that arguably meet the definition.

[27] Di Cesare et al., *World Heart Report 2023*.

[28] Bostrom and Ćirković, *Global Catastrophic Risks*, p. 27.

[29] Compare this definition with the World Economic Forum's definition of *global risk*: "the possibility of the occurrence of an event or condition which, if it occurs, would negatively impact a significant proportion of global GDP [gross domestic product], population or natural resources" (World Economic Forum, "Global Risks Report 2023," p. 5).

National-Level Risk

In the National Threat and Hazard Identification and Risk Assessment, FEMA, in collaboration with partners throughout the federal government, assessed the effects of the most-catastrophic threats and hazards to the United States, including natural hazards, technological hazards, and adversarial threat.[30] Each of these national-level events has an associated consequence threshold (the consequence categories include economic effect, number of fatalities, and psychological effect). Despite the severity of these events, the consequences relate to U.S. domestic or national-level effects and thus are narrower in scope than the global effects of primary relevance here.

Systemic Risk

Other related concepts are less focused on the scope of a risk and focus instead on the mechanism or means by which a risk propagates. For instance, the concept of systemic risk has been of analytical importance to U.S. and international policymakers, especially in the context of global market failures and supply chain risks. Citing a definition from Jonathan Welburn and Aaron Strong, DHS has identified systemic risk as occurring "when risk is spread across interdependent systems so that a failure of one component has consequences system wide, amplifying the impact of the incident."[31]

Presumably, global catastrophic risks have this spreading, systemwide effect. Indeed, per the GCRMA, catastrophic events can result in "systemic failure . . . of critical infrastructure."[32] Furthermore, many of the global catastrophic risks discussed here have interaction or convergence effects on other risks (we discuss these interaction effects in Chapter 10). But not every systemic risk reaches the threshold of being a global catastrophe.

Emerging Risk

Similarly, public policy and research organizations have described concepts of emerging risk, which the International Risk Governance Council (IRGC) has defined as "new risks or familiar risks that become apparent in new or unfamiliar conditions."[33] This definition underscores a type of uncertainty associated with how these risks manifest, perhaps because of limited historical frequency or for other reasons. Some of the global catastrophic risks discussed here (e.g., AI-related risks) might have this feature, but others (e.g., risks from asteroids) might lend themselves to more certainty about probabilities and effect.

Polycrisis

Some institutions, such as the World Economic Forum, have analyzed the concept of *polycrisis*, which has to do with the interaction of different risks. For instance, one definition holds that "a global polycrisis occurs when crises in multiple global systems become causally entangled in ways that significantly degrade human-

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[30] For details on FEMA's threat and hazard identification and risk assessments, see FEMA, "National Risk and Capability Assessment." See also FEMA, *National Preparedness Report*, for how FEMA has integrated these assessments into its disaster management policy.

[31] Cybersecurity and Infrastructure Security Agency, "Systemic Cyber Risk Reduction Venture," p. 1; Welburn and Strong, "Systemic Cyber Risk and Aggregate Impacts."

[32] U.S. Code, Title 6; Section 821(7), Global Catastrophic and Existential Threats.

[33] IRGC, *IRGC Guidelines for Emerging Risk Governance*, p. 7.

ity's prospects."[34] Interacting crises "produce harms greater than the sum of those the crises would produce in isolation," so new or additional harms emerge from interactions among risks.[35]

Disproportionate Risks

The Biden administration, like others, has prioritized disproportionate risks to socially vulnerable populations in a variety of contexts, such as environmental policy and disaster mitigation.[36] Many risks that policymakers routinely discuss are disproportionate risks because vulnerable communities tend to have fewer resources to prevent harmful outcomes or recover if the risk manifests. In addition, these communities tend to be underrepresented or neglected in deliberations that develop risk-prioritization strategies, so they might be neglected in the decisions that determine policies and resourcing intended to mitigate harms.

The definitions of *existential risk* by Bostrom and others reference the geographic scope of effect. However, they do not consider the distribution of effect—that is, which specific communities or geographies the risk harms. Many of the processes and institutional disruptions that might lead to human extinction, as well as other non–extinction-level catastrophes, will likely disproportionately affect vulnerable communities. For instance, the U.S. Environmental Protection Agency has discussed how climate change has a disproportionate effect on vulnerable communities.[37] Per the discussion in the next section about risk prioritization, the fact that a risk is catastrophic or even existential does not necessarily mean that it should be the only priority in public policy, and disproportionate risks, as well as national-level and other risks, might need to be appropriately balanced.

Perceptions of Global Catastrophic Risks and Their Importance

Bostrom's framework describing risk in terms of intensity and geographic scope helps focus attention on factors that differentiate global catastrophic and existential risks from other risks. These dimensions (intensity and geographic scope) tend to be associated with threats and hazards responsible for immense fatalities and other harms. And although conventional thinking would suggest that greater risk motivates greater action and response, the relationship between how people perceive risk and the decisions they make to manage risk, as well as their support for various government responses, is more complicated than that. Complex factors in human psychology, context, the characteristics of the risks themselves, and underlying normative and ethical commitments influence risk management decisions.

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[34] Lawrence, Janzwood, and Homer-Dixon, *What Is a Global Polycrisis?* p. 2. See also World Economic Forum, "Global Risks Report 2023," in which polycrises are described as situations in which "disparate crises interact such that the overall impact far exceeds the sum of each part" (p. 9).

[35] Lawrence, Janzwood, and Homer-Dixon, *What Is a Global Polycrisis?* p. 2.

[36] See Biden, "Executive Order on Advancing Racial Equity and Support for Underserved Communities Through the Federal Government"; Biden, "Executive Order on Further Advancing Racial Equity and Support for Underserved Communities Through the Federal Government"; DHS, "Advancing Equity at DHS"; EPA, "EPA Report Shows Disproportionate Impacts of Climate Change on Socially Vulnerable Populations in the United States"; Office of Atmospheric Programs, *Climate Change and Social Vulnerability in the United States*; and White House, "Justice40."

[37] Office of Atmospheric Programs, *Climate Change and Social Vulnerability in the United States*; EPA, "EPA Report Shows Disproportionate Impacts of Climate Change on Socially Vulnerable Populations in the United States."

Perceptions of Risk

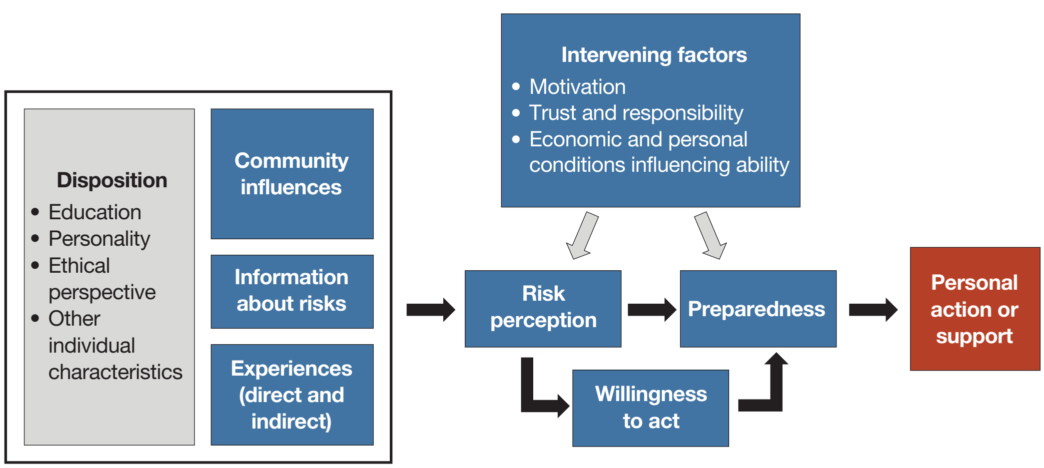
Human cognition and perception make decisions about managing global catastrophic and existential risk challenging. The extreme intensity and scope of these outcomes can be difficult to adequately plan for and comprehend. Citing decisionmaking theories and empirical studies, Paul Slovic pointed out that "constant increases in the magnitude of a stimulus typically evoke smaller and smaller changes in response" and suggests that this "psychic numbing" can lead people to overlook or underappreciate the risks from events that lead to overwhelming numbers of deaths, such as genocides or nuclear war.[38] To emphasize the practical implication of this effect on risk management, Slovic quotes Nobel Prize recipient Albert von Szent-Györgyi's self-reflection on his inability to comprehend the full consequences of nuclear war:

> I am still touched by any individual suffering and would even risk my life for a fellow man in trouble, but I cannot multiply individual suffering by a hundred million, and so I talk with a smile about the "pulverization" of our big cities.[39]

As Figure 2.1 illustrates, people's perceptions of risk and related decisions are influenced by more than just the *magnitude* of a risk. In addition to accounting for information about risk, people's decisions to act or support are influenced by interactions with others in their communities, their underlying ethical theories, their own experiences or the experiences of others they learn about, their competing motivations, their trust in organizations responsible for risk management, and factors influencing their abilities to manage risk (such as economic and personal conditions). Under certain circumstances, these factors dominate decisions and result in inaction or failure to prepare, even when perceptions of risk are high.[40]

Notwithstanding these influences, some catastrophic risks motivate significant public concern and calls for action. Studies of risk perception help explain that hazards associated with dread and that are believed to be well understood are generally perceived to present higher risks and are associated with stronger calls

FIGURE 2.1
The Hazard-to-Action Chain



SOURCE: Adapted from Wachinger et al., "The Risk Perception Paradox."

[38] Slovic, "'If I Look at the Mass I Will Never Act,'" p. 85.

[39] Szent-Györgyi, "The Brain, Morals, and Politics," p. 3.

[40] Wachinger et al., "The Risk Perception Paradox."

for regulation.[41] Similar studies of risk in different domains (such as technological, health and safety, environmental, and homeland security) have confirmed the relevance of these factors and revealed additional dimensions shown to influence perceptions of risk (see Table 2.1). When describing risks to inform sound risk management, one must address the full array of dimensions that research reveals as having an effect on how people perceive risk and how those perceptions motivate action.[42] The framework described in Chapter 3 reflects this literature.

Ethical Perspectives on Global Catastrophic Risk

The stakes of global catastrophic and existential risks could not be higher. However, there are different ethical views of how much priority people should assign to events with low likelihood yet wide effect. These ethical views might have differing implications for which public policies should be implemented to mitigate

TABLE 2.1
Dimensions That Influence Perceptions of Risk

Type of Risk	Relevant Dimensions
Technological[a]	• Dread risk: uncontrollable, dread, global catastrophic, fatal consequences, not equitable, catastrophic, high risks to future generations, not easily reduced, increasing risk, involuntary exposure, affects oneself • Unknown risk: not observable, unknown to those exposed, delayed effects, new or emerging risk, unknown to science
Health and safety[b]	• Deaths and injuries • Delay of effects • Quality of scientific understanding • Uncertainty about risk • Controllability of exposure
Environmental and ecological[c]	• Deaths and injuries • Delay of health effects • Scientific understanding of health effects • Controllability of health effects • Ecological effects • Aesthetic effects on the environment • Delay of environmental effects • Duration of environmental effects • Scientific understanding of environmental effects • Reduction in ecosystem services to humans
Homeland security[d]	• Deaths, injuries, and illnesses • National well-being • Economic damage • Infrastructure disruptions • Environmental damage • Governance disruption • Frequency of occurrence • Predictability • Uncertainty about risks

[a] Slovic, Fischhoff, and Lichtenstein, "Facts and Fears."
[b] Florig et al., "A Deliberative Method for Ranking Risks."
[c] Willis et al., "Ecological Risk Ranking."
[d] Lundberg, *Comparing Homeland Security Risks Using a Deliberative Risk Ranking Methodology*; Willis et al., *Homeland Security National Risk Characterization*.

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[41] See Fox-Glassman and Weber, "What Makes Risk Acceptable?"; Slovic, Fischhoff, and Lichtenstein, "Facts and Fears"; and Slovic, Fischhoff, and Lichtenstein, "Characterizing Perceived Risk."

[42] Fischhoff and Morgan, "The Science and Practice of Risk Ranking."

global catastrophic risks, how much attention and resources should be dedicated to them, and which tradeoffs in the policy space are justified.

In this section, we describe areas of disagreement about the ethics of managing global catastrophic risk. The goal is to inform policymakers about these underlying disputes and to undergird an approach to assessing global catastrophic risk that hews closely to the language of the GCRMA while accommodating these divergent perspectives. Ultimately, we developed a risk assessment approach intended to be acceptable across these ethical positions and that can provide overarching guidance for policymakers.[43]

Utilitarianism

The ethical theory of utilitarianism—the view that right actions are those that produce the most overall utility—has a straightforward explanation of why one should prioritize global catastrophic and existential risks. Under certain assumptions, there could be perhaps 80 trillion more people.[44] And if quality of life increases as it has in the past millennia, these future people might be able to live very good lives.

This line of thinking underscores a type of policy approach that leverages expected value and cost-effectiveness calculations. These calculations evaluate the probability of an event and the expected outcomes from that event to determine an overall expected value of that event. And integrating this within the utilitarian ethical framework, right actions and policies are those that produce the greatest expected utility. In this view, policies should prioritize preventing events with a large scope of effect, even if they are very low probability, because those events might have a massive effect on human existence.[45] Per Nick Bostrom, "the objective of reducing existential risks should be a dominant consideration whenever we act out of an impersonal concern for humankind as a whole."[46]

Arguments Against Utilitarianism

There are well-known objections to the utilitarian view and its implications for public policy, including that it has some counterintuitive implications.[47] Consider political scientist Joseph Nye's objection that the utilitarian view subjects people's decisions today to a "dictatorship of future generations over the present one."[48] In

[43] A comprehensive discussion of philosophical approaches is beyond the scope of this report. We focus on utilitarianism, as well as several alternative accounts, including contractualism and virtue ethics, because of the central role of these views in contemporary discussions of existential risk.

[44] MacAskill, *What We Owe the Future*.

[45] For instance, Jason Matheny has discussed events that "extinguish humanity" and argued that, "while the probability . . . may be very low, . . . the expected value of preventing them could be high, as it represents the value of all future human lives" (Matheny, "Reducing the Risk of Human Extinction," p. 1335).

[46] Bostrom, "Existential Risk Prevention as Global Priority," p. 19.

[47] For instance, philosopher Derek Parfit has argued that utilitarian approaches that call on people to maximize total welfare would imply the "repugnant conclusion" (Parfit, *Reasons and Persons*, pp. 387–390) that humans should populate the world with very large numbers of people, even if those people live very bad lives (Parfit, *Reasons and Persons*). There are responses to this implication, such as forms of utilitarianism that focus on promoting the greatest average utility rather than aggregate sum. But even these views face counterintuitive consequences about the types of future population distributions one should promote (see, e.g., MacAskill, *What We Owe the Future*). Note that ultimately, William MacAskill argued that Parfit's "repugnant conclusion" is not such a bad pill to swallow.

[48] Nye, *Nuclear Ethics*, p. 64. Nye continued, "If we care about other values in addition to survival, this crude utilitarian approach produces intolerable consequences for the current generation" (Nye, *Nuclear Ethics*, p. 64). That is, focusing on future people potentially means that present people might take actions that "may reduce the meaning of life to some people in the current generation, that is a value to be judged against others in assessing the risks that are worth running for this generation" (Nye, *Nuclear Ethics*, p. 65).

other words, utilitarianism requires that present people bring about the actions with the most overall utility, even if that requires sacrificing the well-being of people today.

Many thinkers have emphasized the point that prioritizing existential risk could mean that present people neglect today's pressing challenges.[49] This concern has been raised in the context of responses to climate change in which near-term harms, and even unrecoverable collapse, are already happening for many of the world's most-vulnerable populations. It also arises in the context of AI, in which some have argued that the "hype" that AI could lead to catastrophe diverts limited governmental resources and attention away from AI's existing harms, such as privacy infringements, inequity, political polarization, and truth decay.[50]

There are also objections that the utilitarian requirement to calculate the welfare of trillions of potential people stretches moral sympathy and cognitive abilities in ways that are not psychologically realistic. Utilitarian approaches might not adequately explain people's strong motivations to care for family, friends, compatriots, and other personally known contemporaries. And it might dilute present people's motivations and emotional connection to people here and now, treating them as a tool in a future-oriented, causal moral calculus.[51]

Alternatives to Utilitarianism

Some alternatives to utilitarianism center on such concepts as justice and human rights and offer different priorities for public policy. For instance, theories that situate morality within social contracts (e.g., forms of contractualism) or in the cultivation of human virtues (e.g., in the virtue ethics tradition) might mean that present people have reasons to prioritize the high-probability events that already affect living today, especially when they affect people who are socially vulnerable.[52] Instead of prioritizing low-probability, wide-scope events associated with existential risk, these views might support prioritizing the events affecting people with whom one shares community and for whom one thus has special responsibilities.

There are also objections to these nonutilitarian views. For instance, some argue that they might be too parochial and allow too much partiality in ways that do not appreciate the importance of extending the scope

[49] Per Émile Torres, the consequentialist approach "nontrivially increase[s] the probability that actual people—those alive today and in the near future—suffer extreme harms, even death" (Torres, "Against Longtermism"). See also Richards et al., "The Illusion of AI's Existential Risk."

[50] See, for example, O'Shaughnessy, "How Hype over AI Superintelligence Could Lead Policy Astray":

> [A]re superintelligence concerns diverting resources from concrete and longstanding AI policy challenges? In theory, policymakers would be able to address both evolutionary risks of AI and hypothetical superintelligence risks. But in reality, limited attention, resources, and political capital often force prioritization.

Or this editorial from *Nature*:

> The idea that AI could lead to human extinction has been discussed on the fringes of the technology community for years. The excitement about the tool ChatGPT and generative AI has now propelled it into the mainstream. But, like a magician's sleight of hand, it draws attention away from the real issue: the societal harms that AI systems and tools are causing now, or risk causing in future. ("Stop Talking About Tomorrow's AI Doomsday When AI Poses Risks Today," p. 885)

Or Joy Buolamwini:

> Existing AI systems that cause demonstrated harms are more dangerous than hypothetical "sentient" AI systems because they are real . . .. One problem with minimizing existing AI harms by saying hypothetical existential harms are more important is that it shifts the flow of valuable resources and legislative attention. (Buolamwini, *Unmasking AI*, pp. 151–152)

Or Kamala Harris: "Let us be clear, there are additional threats that also demand our action. Threats that are currently causing harm, and which to many people also feel existential" (Harris, remarks on the future of intelligence).

[51] See, relatedly, the "one thought too many" critique of utilitarianism in Smart and Williams, *Utilitarianism For and Against*.

[52] See Rawls, *A Theory of Justice*. For further reading on forms of contractualism, see Scanlon, *What We Owe to Each Other*; Táíwò, *Reconsidering Reparations*; and Rawls, *A Theory of Justice*. For more about virtue ethics, see Annas, *Intelligent Virtue*; Foot, *Natural Goodness*; and Hursthouse, *On Virtue Ethics*.

of ethical consideration in an impersonal way across humans' possible future. Another broad challenge to nonutilitarian views is that they do not typically use expected value calculations as a guide to public policy, so they might be less clear about which policies should be prioritized.

A Way Ahead

Some factors influence perceptions of risk, as well as foundational, normative commitments in population ethics that support alternative views of the extent to which policy should prioritize low-probability and wide-scope events. These complex factors and fundamental disagreements will likely persist, so there are grounds to consider approaches to global catastrophic risks that do not preclude or dismiss reasonable perspectives. For instance, policymakers can consider whether attention to preventing global catastrophic risks interferes with policies that address current harms. Similarly, there are reasons to think seriously about global catastrophic risks if society might have an opportunity to prevent or mitigate them.

We developed a risk assessment framework that we explain in Chapter 3 that is intended to accommodate these ethical views and to provide a foundation for an overlapping consensus approach among reasonable viewpoints to assess global catastrophic risks.[53] Our framework supports the development of risk mitigations that guard against both near-term risks affecting people today and long-term risks that are decisive for the future of humanity. With this approach, we seek to identify shared implications of different views that public policy can implement—for instance, fostering resilient communities with healthier environments that are better prepared for both the ongoing disasters of today and the disasters that could lie ahead.

[53] The concept of an overlapping consensus among reasonable views is discussed in detail in Rawls, *Political Liberalism*.

CHAPTER 3

Risk Frameworks and Approach

The GCRMA instructs the administrator of FEMA and the Secretary of Homeland Security to coordinate on an assessment of global catastrophic risks (Section 7303 of the act).[1] One key purpose of the assessment is to enable these officials, in collaboration with a wide variety of federal agencies and other partners, to develop strategies to better manage these risks (Section 7305 of the act).[2]

The breadth of threats and hazards covered in the act—AI, asteroid and comet impacts, severe climate change, nuclear war, pandemics, and supervolcanoes—requires establishing a common framework for presenting risk-relevant information that facilitates comparison across the risks of interest. Because the broader goal of the GCRMA is to reduce risks to human civilization, this assessment must be conducted in a manner that serves that larger purpose. Additionally, any framework used to assess and manage these risks should enable policymakers to weigh multiple consequence dimensions, which, as discussed in Chapter 2, affect how risks are perceived and govern the extent to which and how people productively engage in taking risk-mitigating and risk-accepting actions.

The Global Catastrophic Risk Management Act Risk Assessment Framework

Each assessment of individual global catastrophic risks is organized around a set of questions focused on the processes that could generate adverse effects on the scale of a global catastrophic risk, the varied consequences of such effects, potential responses, and the nature of the evidence. Each assessment begins with an examination of the natural and human processes that combine to create the risk in question, allowing for various ways in which the risk might unfold—we term these potential futures *pathways*.

Each assessment then considers the potential consequences of the risk pathways in the following four categories:

- *mortality*, which is the rough number (order of magnitude) of human fatalities that might be expected
- *ecosystem instability*, which is the disruption to the natural environment and ecosystem functions that create an inhabitable Earth and support ecosystem services on which humans depend
- *societal instability*, which we define as disruptions to economic and governance systems[3]

[1] Public Law 117-263, Section 7303, Assessment of Global Catastrophic Risk.

[2] Public Law 117-263, Section 7305, Enhanced Catastrophic Incident Annex.

[3] We used FEMA, "FEMA National Continuity Programs," as a starting point for articulating the governance dimension of societal instability.

- *reduced human capability*, which, drawing from Nussbaum's taxonomy of human capability, we define as a degradation in key dimensions of human well-being, such as bodily health and integrity, affiliation, and control over one's environment.[4]

Each assessment also includes a discussion of uncertainties, the timing of the risk, whether and how the risk is anticipated to change in the next decade, and the types of actions that have been taken or could be taken to reduce the risk.

Our motivation for considering consequence categories beyond mortality is that mortality alone is an insufficient metric for deciding whether a risk constitutes a catastrophe. Catastrophe can take many forms. For instance, a risk that leads to few deaths (in comparison with human extinction) but that destabilizes governance and social structures so greatly as to bring civil society to a grinding halt could be considered catastrophic. In taking this more-expansive view of catastrophe, we hope to identify opportunities for managing risks that a framework focused singularly on numbers of lives lost might overlook.

Furthermore, the four categories used in this assessment enable representation of the broad variety of outcomes that those who have researched risk perception have identified as important for understanding how people perceive and respond to risks. These studies, cited in Table 2.1 in Chapter 2, reflect insights from multiple, overlapping risk management policy domains. Researchers studying managing risks from technologies and risks to health and safety have identified the importance of capturing mortality and morbidity effects, as well as the timing of and uncertainty about those effects. Studies on environmental risks have noted the importance of adding information on outcomes related to ecological systems (including effects on species and habitats), ecosystem services (that is, the benefits that healthy ecosystems convey to humans), and the aesthetic perspectives of natural environments. Studies of homeland security risks added treatment of disruptions to economic and governance systems and the effects on societal well-being. As discussed in Chapter 2, consideration of societal well-being in the context of risks that could threaten human civilization can be expanded to consider a reduction of human capabilities.

Table 3.1 provides an overview of these consequence categories and scales relevant for assessing each. Together, these four consequence categories are sufficiently broad to accommodate consideration of the spectrum of factors that the risk perception literature indicates influences how people judge and manage risks introduced in Chapter 2 and that might be associated with the risks considered in this report even if they are not named specifically in Table 3.1. For instance, such consequences as morbidity and species loss can be considered under one of the four broader categories (e.g., human capability and ecosystem instability, respectively). The columns of Table 3.1 offer values that the intensity or magnitude of each consequence category could take.

As events that threaten civilization unfold, over time, society would likely experience consequences across all four categories of risk. That said, we have scoped the assessments presented in subsequent chapters to focus on the *direct* effects of the hazards in question, acknowledging that *indirect* effects also merit consideration.

Figure 3.1 sketches the relationships among potential events (such as the natural and anthropogenic risks considered in this report), four categories of direct effects (not catastrophic, catastrophic, civilization collapse, and human extinction), and whether humanity would recover from each of these effects. Logically, humanity could recover from a noncatastrophic effect, but they could never recover from extinction of the

[4] Nussbaum, *Creating Capabilities*. Although Nussbaum included several other dimensions in her taxonomy, we focus on these because they are particularly relevant to the risks covered in this report. Reduced human capability is the most difficult of the four consequence categories to clearly define because it requires confronting such questions as what it means to be human and, in turn, what people would collectively view as a reduced state of humanness. Rather than attempt to precisely define and measure this dimension, we include it simply as an aspect to consider, allowing the category to flexibly accommodate different theoretical conceptions of the idea.

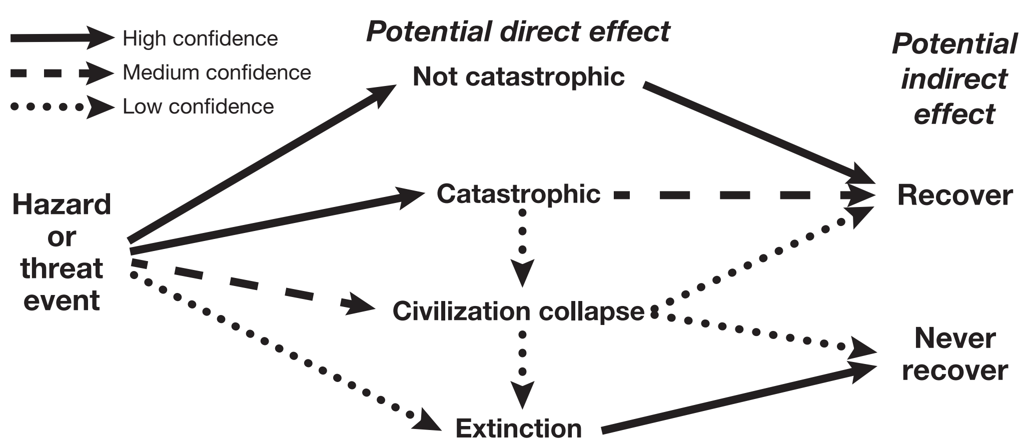
TABLE 3.1

Relevant Dimensions for Assessing Consequences of Different Types

Consequence Category	Human Fatalities Within a Few Years	Intensity	Geographic Extent	Duration
Mortality	• Millions or fewer • Tens of millions • Hundreds of millions • Billions or more	Not applicable	Not applicable	Not applicable
Ecosystem instability	Not applicable	• Less-than-significant degradation of ecosystem function or services • Significant degradation of ecosystem function or services • Shift to a fundamentally different ecosystem equilibrium • Destruction of the ecosystem	• Regional or less • Continental • Hemispheric • Global	• Months or years or less • Decades • Centuries or more
Societal instability	Not applicable	• Economic losses of varying extents • Governance failures of varying degrees		
Reduced human capability	Not applicable	• Less-than-significant diminishment of (some) human capabilities • Significant diminishment of (some) human capabilities • Complete diminishment of all human capabilities		

FIGURE 3.1

Confidence Levels in Estimated Effects of Global Catastrophic Risks



NOTE: Most of the confidence discussion in our chapters involves direct effects.

species. Figure 3.1 notes our judgments of the current state of knowledge of the processes by which a catastrophic or existential risk might lead to civilization collapse or extinction and from which humanity does or does not recover. The figure represents these judgments using a confidence scale—high, medium, and low—as employed in many scientific assessments.[5] We have high confidence that extinction would be permanent and that humans can recover from noncatastrophic events. There is some historical evidence and understanding of how humans have recovered from past catastrophes, so we have medium confidence in our understanding of such future processes. We have low confidence in the understanding of other transitions in Figure 3.1.[6]

The concept of *net risk*—the remaining or residual risks after accounting for the benefits afforded by the source of a risk and any actions taken to mitigate it—applies to some of the risks in question. For example, when making decisions about how to manage the risk of using AI, any adverse consequences should be weighed against the benefits of employing the technology. Similarly, interventions, such as geoengineering and decarbonization technologies, could reduce the risk from climate change. On the other hand, asteroids, comets, and supervolcanoes do not inherently offer benefits to society, nor are there mature technological or governance options for preventing or responding to these hazards. As such, net risk is a less relevant concept for assessing and managing these risks. We draw special attention to the idea of net risk in the chapters related to pandemics (Chapter 6), climate change (Chapter 7), and AI (Chapter 9).

Chapter 10 plots each of the six risks on a quad chart that considers two dimensions: the geographic extent of consequences and the quality of evidence about the risk. The chapter then provides guidance on the most-appropriate management strategies for risks that fall into each quadrant.

Global Catastrophic Risks and Uncertainty

In general, it is difficult to know in advance whether humans would survive or recover from a specific catastrophe and therefore whether its risk is existential, catastrophic, or something else altogether. The information available on global catastrophic risks is far from perfect. In many cases, strategies for managing global catastrophic risks face conditions of deep uncertainty in which any probability estimates are, at best, necessarily imprecise, and the consequences of potential risk management actions are, at best, imperfectly understood or recognized ignorance where even the possible outcomes are not identifiable.[7] Deeply uncertain processes can, however, have significant policy implications, so they are important to consider lest one succumb to the proverbial fallacy of looking under the lamppost for risk management solutions.

Some sources of this uncertainty are related to factors that are, in principle, known or knowable, even if the knowledge is not currently available. For this type of uncertainty, *aleatory* uncertainty, evidence can be defined and feasibly obtained to allow characterization of variation in outcomes or the likelihood of events occurring. And, when evidence is not available, scientific research can improve understanding of the physical, natural, and societal phenomena that lead to risks. For example, celestial observation and application of orbital modeling allow estimation of the probability of impact of large meteors or comets on Earth.

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[5] Begum et al., "Point of Departure and Key Concepts," Section 1.3.4; Janzwood, "Confidence Deficits and Reducibility"; Mach et al., "Unleashing Expert Judgment in Assessment."

[6] Low confidence is not a proxy for low probability. The opposite of low probability is high probability. In contrast, the opposite of low confidence in one outcome does not imply high confidence in the opposite outcome. Rather, low confidence implies that, although we report the best current understanding of a process, that understanding could easily change in the future.

[7] Janzwood, "Confidence Deficits and Reducibility."

In contrast, another form of uncertainty—*epistemic* uncertainty— involves factors that are both unknown and not knowable. For example, although experts can posit how likely a nuclear war is, the true probability of such events is not knowable. Many complex systems exhibit emergent behaviors hard to predict ex ante with any confidence. Yet, in some cases, scientific research can convert unknown topics to the realm of the known, thus turning epistemic uncertainty into aleatory uncertainty. For example, continued research into atmospheric and climate sciences might improve understanding of whether and how some extreme climate change could occur or be avoided.

Why We Do Not Focus on Probabilities

Although risk is often usefully calculated as the product of probability and consequence, not all six assessments provide such estimates, nor do probabilistic estimates represent the primary deliverable in each of the six assessments. Because some readers might expect probabilistic estimates to be central to a report on global catastrophic risks, it seems appropriate to explain our reasoning.

First, the evidence base for estimating such probabilities is sparse for many civilization-threatening risks for a variety of reasons. Some risks (e.g., AI) are entirely novel. Other risks (e.g., supervolcanoes) have historical precedent, but those precedents are infrequent and in the distant past. And other risks (e.g., rapid and extreme climate change) result from processes that are poorly understood. Some approaches, such as structured elicitations—which can offer a way to estimate likelihoods when experts lack sufficient quantitative evidence to support the direct calculation of probability distributions—would likely fall short in the context of very new or very poorly understood risks. For such risks, given the sparse evidence, we would have low confidence in probability estimates derived from *any* source for the foreseeable future.

Second, risk quantified as the product of probability and consequence is frequently used to facilitate the comparison of different risks. The six global catastrophic risks in this study arise, however, from vastly disparate types of processes. Our understanding of these processes draws from quite different bases of evidence. These risks include

- risks from low-frequency natural processes that have caused catastrophic effects for life on Earth in the distant, prehuman past. These risks include
  - supervolcanoes
  - impacts from space objects, such as asteroids and comets
- risks from human processes, with which people have been living for decades or centuries but whose character is changing. These risks include
  - pandemics, which have had globally catastrophic effects in the past. The risk of future pandemics increases with such factors as ease of global travel, expanding human contact with disease-carrying animals, and advances in biotechnology enabling design of pathogens. The risk decreases with such factors as improvements in medical technology.
  - climate change, which has intensified because of economic activity organized around today's technologies and patterns of human behavior but effects of which have long been felt and are only likely to worsen
  - nuclear war, whose frequency is influenced by many factors, including proliferation of nuclear weapons and how arms control and possession of nuclear weapons might have contributed to their use
- risks from novel human processes, which arise from the adverse consequences of humans pursuing their goals. These processes have not yet caused catastrophic effects, but the risks appear to be increasing. These risks include
  - AI, a field that is rapidly advancing as humans seek beneficial advances in technology.

Given that the set of risks covered in this report vary considerably, a focus on probabilistic estimates as the primary means to compare them would submerge more information than it would reveal. The approach chosen here—a common set of questions focused on processes, consequences, actions, and evidence—has support in the literature for assessments under analogous circumstances. The focus on processes and consequences, sometimes labeled *storyline* in the literature,[8] has multiple advantages in situations with insufficient evidence to support comprehensive, probabilistic risk assessment. The approach improves risk awareness by framing risk in an event-oriented rather than probabilistic manner, which corresponds to how people perceive and respond to risk. It partitions the uncertainty by enabling analysts to identify the parts of the causal chains that are more and less understood. It can inform decisionmaking by suggesting a variety of appropriate intervention points, supports the development of dynamic adaptive pathways, and supports stress tests of current and proposed risk-reducing actions. These stress tests, in turn, enable iterative recrafting and realigning of the actions until they can manage the risks as well as possible. Each of these features helps support the consideration of multifaceted, dynamically adaptive, all-hazards strategies. The approach of laying out the exposition of each risk in a common format treats each risk assessment as a case study, thereby enabling systematic, structured, focused comparison for each of the risks.[9]

The next section describes two risk frameworks that influenced our approach to identifying risk mitigation options (which we briefly discuss as part of each risk summary) and proposing the broader risk management strategies detailed in Chapter 10.

Risk Management Frameworks

Because the GCRMA is ultimately focused on risk management, we considered two risk frameworks related to the mitigation and management of global catastrophic risk in development of this risk assessment approach and interpretation of the findings of this report. The first is attributable to M. Granger Morgan and focuses more narrowly on the task of *managing* (technology-induced) risks.[10] The second was developed by the IRGC and covers the breadth of analytic and engagement aspects requisite for sound risk *governance*, including risk assessment, which is our focus. Our focus on these two frameworks should not be taken to mean they are the only relevant ones for addressing the sorts of risks covered in this report. Federal policy, executive orders, frameworks, and interagency approaches at multiple levels of government spanning disciplines, as well as international frameworks and approaches with which the United States is involved, also inform such risk assessments and associated mitigation activities and are conceptually consistent with these two frameworks.

Framework for Managing Technology-Induced Risks

Because a global catastrophic risk management strategy can employ a diverse array of types of actions, thinking broadly about opportunities to intervene to manage risks is necessary. Morgan offered one taxonomy of processes, each of which suggests different types of actions for managing technology-induced risks.[11] The taxonomy shows that risk can emerge from the interaction of the natural and human environments. The taxonomy differentiates among processes of exposure, effects, human perception, and human valuation. Exposure processes arise from interactions between human and natural systems that put people, their livelihoods,

[8] Shepherd et al., "Storylines."

[9] George and Bennett, *Case Studies and Theory Development in the Social Sciences*.

[10] Morgan, "Risk Assessment."

[11] Morgan, "Risk Assessment."

infrastructure, natural systems, and other economic and cultural assets in places and settings that could be adversely affected. Effect processes, under the right conditions, manifest these adverse effects. Human perception processes determine how any adverse effects influence core functions or systems that humans value, and human valuation processes can reduce or modify these effects on human values.

This taxonomy proves useful because humans might be able to intervene in at least several of these processes to reduce risk. Opportunities might exist to reduce or prevent the onset of a threat or hazard occurring. When that is not possible or successful, opportunities might exist to disrupt the mechanisms that lead to generation of harmful consequences. To complement these strategies, opportunities might exist to reduce the severity of effects should they occur. And, when all else fails, options exist to recover from the effects.

For instance, as shown in the notional example presented in Table 3.2, the interaction of potentially large solar storms with the use of electric grids could create significant risks for communities that could be mitigated in several ways. This risk could be reduced if humans shifted to energy sources other than electricity, thereby reducing the exposure process. However, doing so could prove so costly that other strategies are preferable. In this case, humans could also locate electrical systems deep underground; otherwise harden them from the effects of solar radiation; or deploy monitoring and control systems that could depower and protect electrical systems on warning of solar storms; thereby reducing exposure processes. Implementing redundant or alternative infrastructure systems presents additional strategies to manage risks, such as stockpiles of high-voltage transformers, which have long production cycles, or distributed microgrids, which could increase system resilience. Maintaining large stocks of nonperishable food and supplies along with effectively and adequately funded response operations (enabled, for instance, through functioning transportation and distribution networks) might enable people to remain adequately fed and to sustain themselves until electrical systems were restored, thereby reducing human perception processes. Finally, enhancing recovery capabilities so that any damaged electric systems could be more quickly repaired would reduce the effect on human values. Each of these types of actions places information demands on a risk assessment, which can be met by being specific in describing the pathways through which risks manifest. Specifying exactly how a risk unfolds or could unfold can shed light on where along the risk pathway a risk mitigation of a given sort might be most effective.

International Risk Governance Council Framework

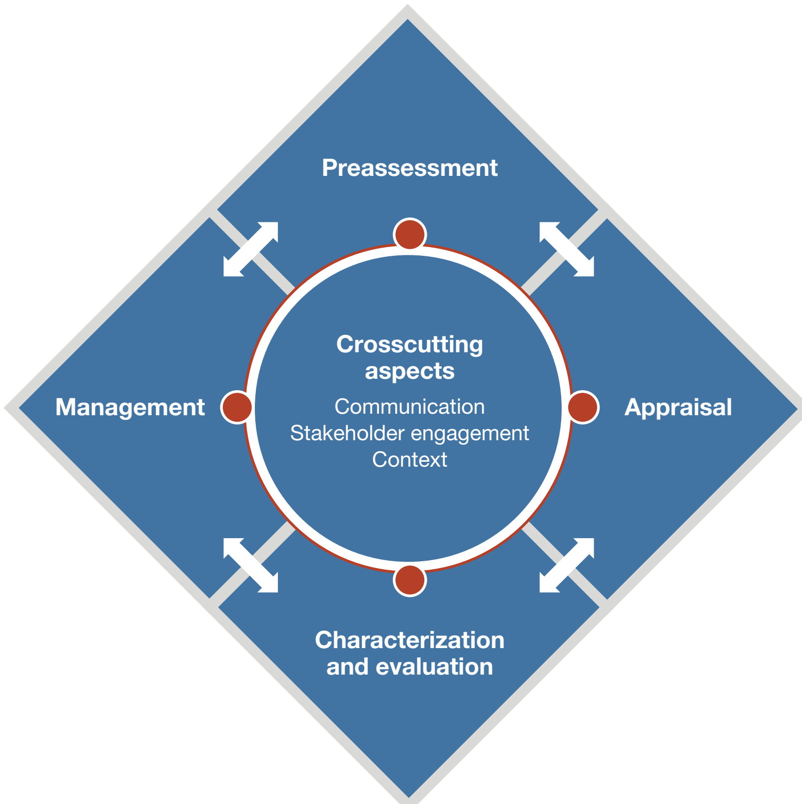
Figure 3.2 shows key elements of the IRGC framework.[12] Of particular relevance to our effort are the interconnected governance processes involved in understanding and mitigating risks, which are depicted in the

TABLE 3.2
Potential Risk Management Options for Severe Solar Storms

Mitigation Dimension	Potential Mitigation Strategy
Reduce the likelihood of occurrence.	• Avoid the use of electricity, or use other types of energy.
Disrupt the mechanisms leading to risk.	• Harden electronic systems so they are insulated from effects. • Implement monitoring and control systems to depower electricity systems automatically on warning.
Reduce the severity of effects.	• Maintain stockpiles of electronic equipment, such as high-voltage transformers. • Deploy distributed microgrids.
Enhance response and recovery.	• Maintain stockpiles of food and supplies, and operate and fund effective recovery operations.

[12] Florin and Bürkler, *Introduction to the IRGC Risk Governance Framework*.

FIGURE 3.2
International Risk Governance Council Framework for Risk Governance



SOURCE: Adapted from Florin and Bürkler, *Introduction to the IRGC Risk Governance Framework*, p. 9.

framework. Although this report focuses primarily on risk assessment, it is intended to ultimately support risk mitigation and governance, which involve evaluating societal concerns about the risks; judging the seriousness and tolerability of the risks; and identifying, assessing, and prioritizing options for managing the risks. As a result, the IRGC framework provides a holistic view of the many aspects of risk governance that will need to be considered in turning the results of this and other assessment-focused efforts into policy actions. In particular, this report focuses largely on the preassessment and appraisal stages of risk governance, setting the stage for future work on characterization and evaluation and on risk management.

Furthermore, although the GCRMA has narrowly identified the six threats and hazards covered in this report, as discussed in the first chapter, society has already faced other global catastrophic or existential risks, or they could emerge at any time. Thus, governance of this class of risks necessitates continued scanning for emergence of new threats and hazards and reassessment of problem framing to ensure societal interests and concerns are being addressed fully—an aspect that is covered in the preassessment stage of the IRGC framework.

For the risk assessment stage itself, we have attempted to capture the different levels of complexity, ambiguity, and uncertainty inherent to each risk in its characterization,[13] the structure of which we describe in greater detail earlier in this section.

Finally, in the latter stages of risk governance, communication and stakeholder engagement are necessary to ensure that societal concerns are captured in how the effects of risks are measured and valued and how priorities are set for managing risks, accounting for the competing benefits and costs of risk management. Of relevance to this effort is the importance of ensuring that assessments, including ours, of global catastrophic and existential risks properly reflect the full set of outcomes that influence concerns raised in Chapter 2, the uncertainty about the risks, the broader landscape of risks (including those society confronts on a regular basis) within which these risks sit, and the benefits generated alongside the risks.

Chapters 4 through 9 present risk summaries for the six risks within the scope of this report, presented in three groups:

- risks from low-frequency natural processes that have caused catastrophic effects on life on Earth in the distant, prehuman past (supervolcanoes and impacts from space objects, such as asteroids and comets)
- risks from human processes, with which people have been living for decades or centuries but whose character is changing (pandemics, climate change, and nuclear war)
- risks from novel human processes, which arise from the adverse consequences of humans pursuing their goals (use of AI).

The six risk summaries share a core structure from which they depart at times to offer additional insights or nuances that were necessary to communicate all relevant information for a given risk.

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[13] We share the IRGC's definitions of *complexity* as "difficulties in identifying and quantifying the causes of specific adverse effects" (Florin and Bürkler, *Introduction to the IRGC Risk Governance Framework*, p. 17), *ambiguity* as the result of "divergent perspectives on the risk" (Florin and Bürkler, *Introduction to the IRGC Risk Governance Framework*, p. 18), and *uncertainty* as "a lack of scientific or technical data, or a lack of clarity or quality of the data" (Florin and Bürkler, *Introduction to the IRGC Risk Governance Framework*, p. 18).

CHAPTER 4

Supervolcanoes: Summary of Risk

Supervolcanoes are volcanoes that produce extremely large, violently explosive eruptions on a scale never experienced by modern humans.[1] Depending on where they are, supervolcano eruptions can cause great damage from both the pyroclastic flow and ash plume that is injected into the atmosphere and dispersed up to hundreds of kilometers away from the eruption site, as well as from emissions of sulfur gases that are injected into the atmosphere and could have a catastrophic effect on Earth's climate.

The term *supervolcano* is relatively new and is generally defined as a volcano that has produced at least one supereruption.[2] A *supereruption*, in turn, is an explosive volcanic eruption producing at least 10^{15} kg of magma, equivalent to about 1,000 km^3 of volcanic deposits—about one-quarter the size of the Grand Canyon—in a short period (i.e., days to weeks).[3] The short-term effects of a supereruption are from pyroclas-

TABLE 4.1

Supervolcanoes: Overview of Risk

Risk Dimension	Assessment for Supervolcano
Most-significant consequences	• Primary: Damage to the natural environment and ecosystem stability • Secondary: Societal instability, deaths, and reduced human capabilities induced by environmental and ecosystem damage
Factors that influence the magnitude of risk	• Proximity of the eruption to populated regions • Sulfur content of gases and crust at the eruption site • Latitude of the eruption site • Onset, speed, and duration of the eruption • For submarine eruptions, depth below the water surface
Likelihood of risk	• Annual exceedance probability of a supereruption (VEI 8): 6.7×10^{-5}, approximate minimum return period of 15,000 years
Temporal nature of the risk and change in the next decade	• Events can be predicted weeks or years in advance. • Regional effects occur immediately. • Pyroclastic flow and ash continue for weeks. • Stratospheric aerosol effects persist for years. • Hazard likelihood and magnitude are unlikely to change.
Quality of the evidence supporting the assessment	• Potentially incomplete geologic record of volcanic activity and sophisticated Earth-system modeling • Inference from observed smaller volcanic eruptions (i.e., VEI less than 8) • Unresolvable variation of when and where a supereruption might next occur • Continued opportunities to improve observation, modeling, and basic scientific knowledge of the phenomenon

NOTE: VEI = volcanic explosivity index.

[1] Large igneous provinces, although much larger in terms of erupted material (i.e., more than 1 million km^3), are generally considered a different hazard from supervolcanoes because their eruptions can extend for hundreds of thousands of years to millions of years (Loughlin et al., *Global Volcanic Hazards and Risk*).

[2] Miller and Wark, "Supervolcanoes and Their Explosive Supereruptions."

[3] Miller and Wark, "Supervolcanoes and Their Explosive Supereruptions"; Sparks et al., *Super-Eruptions*.

tic flows (e.g., magma, rock) and ash. The effects can be devastating on local and regional scales and, depending on the location, a global scale (e.g., if important crop-growing or other production areas are wiped out). Nonetheless, these are likely to be much smaller than the longer-term, global risks posed by the atmospheric aerosols and resulting climate changes.

What Is Known About the Causes of Risk from Supervolcanoes?

What Is a Supervolcano?

Supervolcanoes produce extremely large, violently explosive volcanic eruptions with a VEI value of 8. For comparison, the 1980 Mount St. Helens eruption had a VEI of 5, and the 1991 Mount Pinatubo eruption had a VEI of 6. The VEI scale is logarithmic, meaning that each increasing numeric value represents a tenfold increase in size. Thus, the smallest supereruption would be 100 times the size of Mount Pinatubo and 1,000 times the size of Mount St. Helens. Evidence from the geologic record combined with modeling of global atmospheric and ecological effects demonstrate that supereruptions represent "one of the few natural phenomena that can produce truly global catastrophic effects."[4]

Forty-seven supereruptions have been identified on Earth, although this is a minimum estimate because geologic records are commonly destroyed by erosion or burial.[5] Most of these supereruption records are from the past 50 million years, with the most recent, at Taupō in New Zealand, occurring 26,000 years ago.[6] Most supervolcanoes are associated with a single supereruption (although this could well be an artifact of incomplete preservation), but some—most notably, the Yellowstone supervolcano in the United States—show evidence of multiple events. Supervolcanoes are also known to produce small eruptions of lower VEI values, which can still be devastating.[7]

No evidence suggests that the eruptive mechanism of supereruptions differs in any fundamental way from those of more-familiar, smaller volcanic eruptions. That is, they are essentially very large volcanic eruptions. Explosive eruption mechanisms vary but typically entail a pressure increase in a shallow magma chamber capped by brittle rock. The pressure increase can stem from the formation of gas bubbles (primarily water) or from a rapid injection of fresh magma from below. When the pressure in the chamber exceeds the failure strength of the cap rock, the cap rock eventually fails, often catastrophically, releasing the confining pressure on the magma. The sudden depressurization drives rapid and extensive bubble formation and growth, creating a rapidly rising froth of liquid and gas that shatters explosively as it exits the volcano. This erupting hot mixture of gas, ash (minute fragments of shattered, solidified lava and ash from previous eruptions), and rock particles immediately entrains and heats the surrounding air, creating a column that rises buoyantly to heights in excess of 35 km.[8]

Although most familiar volcanoes are cone-shaped mountains made up of layers of frozen lava from previous eruptions, supervolcanoes undergo eruptions in which magma erupts along a vent around the edge of a large magma chamber in what is called a *caldera-style eruption*. As the enormous volume of magma erupts,

4 Self and Blake, "Consequences of Explosive Supereruptions," p. 41.

5 Miller and Wark, "Supervolcanoes and Their Explosive Supereruptions."

6 Miller and Wark, "Supervolcanoes and Their Explosive Supereruptions."

7 Although the focus of this chapter is on supereruptions of at least VEI 8, we note that lower-VEI eruptions occur more frequently. For instance, VEI 7 eruptions occur once or twice every 1,000 years, still pose significant risk to regional populations, and would result in at least regional disruption to ecosystems, economies, mobility, and climate (Newhall, Self, and Robock, "Anticipating Future Volcanic Explosivity Index [VEI] 7 Eruptions and Their Chilling Impacts").

8 Loughlin et al., *Global Volcanic Hazards and Risks*; Wilson, "Supereruptions and Supervolcanoes."

the roof of the magma chamber descends, often like a piston, resulting in a large, crater-shaped depression, or *caldera*, in Earth's surface. Although not all caldera-style eruptions are necessarily explosive, known super-eruptions appear to have occurred as caldera-style eruptions. The largest confirmed caldera is Toba, on the island of Sumatra, Indonesia, which is 100 km by 40 km and erupted 74,000 years ago.[9] However, the size of a caldera changes over time as it is eroded or undergoes infilling.

The rate and duration of supereruptions are difficult to generalize, although studies of specific cases suggest that eruptive rates are on the order of 109 kg per second and continue, sometimes with interruptions, for days, weeks, or possibly years.[10]

What Are the Mechanisms of a Supervolcano Catastrophe?

Supereruptions are expected to have catastrophic effects both locally and globally. The local effects will be the same as those for smaller, explosive volcanic eruptions, although on a much larger scale. These can include pyroclastic flows and ashfalls, lahars,[11] and tsunamis. Supereruptions also have worldwide effects in the form of global cooling resulting from sulfur dioxide being injected into the stratosphere. In both cases, although particularly at the global scale, the direct effects of a supereruption can lead to indirect effects, which, under certain circumstances, can result in catastrophic losses or even mass extinction. In the rest of this section, we discuss both scales of effect.

Local, Short-Term Effects

Of the numerous possible local effects of a supereruption, experience from known volcanic eruptions indicates that, by far, the most-damaging effects are from pyroclastic flows and ashfalls, so we focus on those in the following sections.

Pyroclastic Flows

Pyroclastic flows are extremely hot, fast, and energetic mixes of volcanic rocks, ash, and gases that flow along Earth's surface radially away from a volcanic vent during an explosive eruption. Pyroclastic flows are driven by gas expansion and gravity and travel at velocities of hundreds of kilometers per hour. Although the flow path is sometimes controlled by topography, particularly large and energetic flows will travel over ridges hundreds of meters high.[12]

A pyroclastic flow is extremely lethal, incinerating and demolishing everything in its path. It can also cause a tsunami when it reaches the sea. Pyroclastic flow deposits from past eruptions can be several hundred meters thick and cover thousands of square kilometers. Pyroclastic flows are responsible for one-third of all volcano-related fatalities, including 28,000 people in the 1902 eruption of Mount Pelée on the Caribbean island of Martinique.[13]

The size of the area affected by pyroclastic flows generally scales with size of the eruption, although it can be influenced by other eruption details. Table 4.2 shows the area of pyroclastic flow deposits from selected historical eruptions. The aerial extent of the largest of these deposits, the Fish Canyon Tuff, is greater than

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9 Miller and Wark, "Supervolcanoes and Their Explosive Supereruptions."

10 Self and Blake, "Consequences of Explosive Supereruptions."

11 A lahar is a violent flow of water mixed with rock fragments ejected from a volcano.

12 Loughlin et al., *Global Volcanic Hazards and Risks*; Self and Blake, "Consequences of Explosive Supereruptions."

13 Neri et al., "Pyroclastic Density Current Hazards and Risk."

TABLE 4.2
Characteristics of Selected Historical Volcanic Eruptions

Caldera	Eruption Deposit	Age, in Millions of Years	Total Erupted Mass, in 10^{15} kg	M[a]	Area of Pyroclastic Flow Deposit, in Square Kilometers
Long Valley[b,c]	Bishop Tuff	0.76	3.5	8.3	2,200
Yellowstone[b,d]	Lava Creek Tuff	0.64	6.6	8.5	7,500
Taupō[b,e]	Oruanui Ignimbrite	0.026	1.4	8.1	8,000
Yellowstone[b,d]	Huckleberry Ridge Tuff	2.1	8.1	8.8	15,500
Toba[b,f]	Youngest Toba Tuff	0.074	6.9	8.8	>20,000
La Garita[b,g]	Fish Canyon Tuff	28	18	9.1	18,000–31,000

[a] The M value listed is the average of the range presented in Mason, Pyle, and Oppenheimer, "The Size and Frequency of the Largest Explosive Eruptions on Earth."

[b] Mason, Pyle, and Oppenheimer, "The Size and Frequency of the Largest Explosive Eruptions on Earth."

[c] Long Valley Caldera, "Bishop Tuff in Long Valley Caldera, California."

[d] Yellowstone, "Summary of Yellowstone Eruption History."

[e] Wilson, "Supereruptions and Supervolcanoes."

[f] Oppenheimer, "Limited Global Change Due to the Largest Known Quaternary Eruption, Toba ≈74 kyr BP?"

[g] Lipman, "Subsidence of Ash-Flow Calderas."

the size of Lake Erie or the state of Vermont.[14] Given the known power of pyroclastic flows, a pyroclastic flow would destroy every structure and kill every person in the area.

Ashfall

Volcanic ash refers to very small—less than 2 mm—erupted rock fragments that can enter the atmosphere and spread across vast regions of Earth via wind.[15] Ash grain size distribution depends on the precise nature of the volcanic eruption because ash is formed when magma is fragmented while depressurizing on its ascent. In the atmosphere, the magma fragments solidify into ash particles composed of a variety of elements, including silicon and oxygen. The extent of ash distribution and fall depends on many factors, including the force of the volcanic eruption, the height of the eruptive column, and the morphology and density of the ash particles, which influence ash buoyancy and aerodynamics. Wind, which varies with altitude, influences the direction of ash transport, allowing ash to spread in all directions.

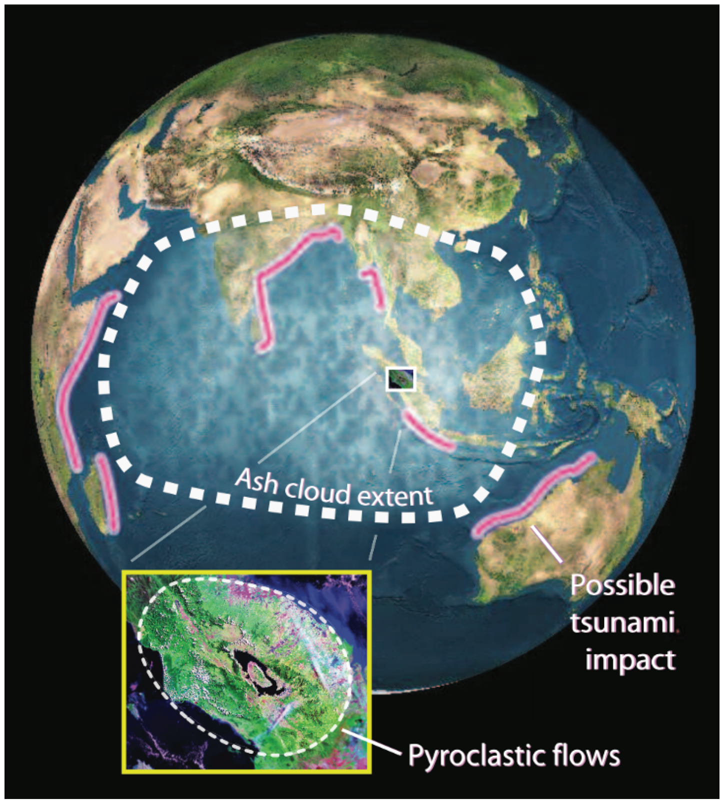
The extent of ashfall from a supereruption could be breathtaking. For example, a layer of ash and pumice fragments from the Toba supereruption covered an area up to 20,000,000 km^2 around the caldera (4 percent of Earth's surface area). The ash layer was up to 200 m thick near the caldera and thinned with distance away. Figure 4.1 shows the extent of the ash deposit from the Toba supereruption. Much of this area is ocean, although large amounts of south and southeast Asia were covered.

A major factor in the effect of ash is eruption location. For instance, a VEI 8–level eruption of Yellowstone caldera in the United States would be highly significant for ashfall. Ashfall models and geologic evidence from the 2.1 million–year-old Yellowstone supereruption reveals that ash covered almost all of what is now the United States west of the Mississippi. The ash produced could have buried the state of California in 20 feet

[14] Aniakchak National Monument and Preserve, "Pyroclastic Flows and Ignimbrites, and Pyroclastic Surges."

[15] Self, "The Effects and Consequences of Very Large Explosive Volcanic Eruptions."

FIGURE 4.1
Toba Ash Cloud Extent



SOURCE: Reproduced from Miller and Wark, "Supervolcanoes and Their Explosive Supereruptions," p. 13.

of ash.[16] More-recent modeling with different assumptions shows that the ash could even have reached New England.[17]

Volcanic ash covering large amounts of land would be highly consequential. The ash could ruin crops and impede agricultural productivity or other land uses for years. In the case of the Yellowstone supereruption, the ashfall covered the majority of what is now U.S. farmland. Everything from Midwest grain to California produce would have been lost for several seasons.

Ash is also harmful to aircraft, and very large ash clouds would likely cause significant degradation to the aviation industry. Ash can enter jet engines and abrade aircraft surfaces, including wings, windshields, and lights. Sensors can become blocked by ash, causing them to provide incorrect readings of critical information. Ash also directly reduces visibility. Mere millimeters of ashfall on runways and taxiways can render an airport unusable until the ash is cleared and contained. Aviation disruptions are not limited to gigantic hypothetical volcanic eruptions. For example, in 2010, the Icelandic volcano Eyjafjallajökull erupted with an estimated magnitude of VEI 3 and stopped air traffic in European airspace for several days.[18]

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16 Bryson, *A Short History of Nearly Everything*.

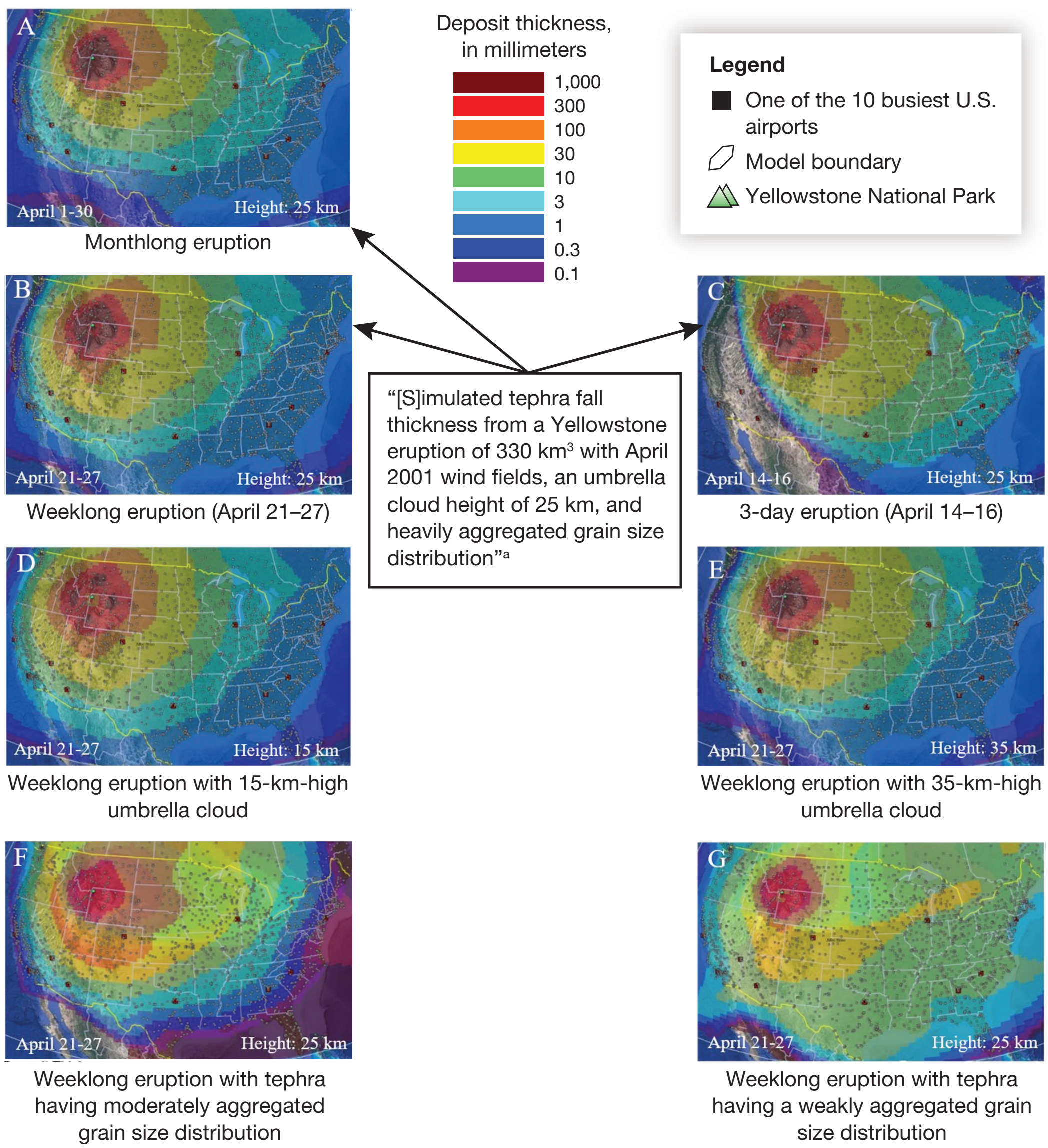
17 Mastin, Van Eaton, and Lowenstern, "Modeling Ash Fall Distribution from a Yellowstone Supereruption."

18 Gudmundsson et al., "Ash Generation and Distribution from the April–May 2010 Eruption of Eyjafjallajökull, Iceland."

Figure 4.2 summarizes Larry Mastin, Alexa Van Eaton, and Jacob Lowenstern's model of ash distribution from a Yellowstone supereruption over time. They demonstrated that it would cause disruption to livestock and crop production in the U.S. Midwest and shut down air travel in North America, among other ashfall-related effect.[19]

Ash can also cause direct effects on human and animal health. Fine ash particles (those less than 10 micrometers in diameter) can cause respiratory distress, as well as irritation to mucous membranes and

FIGURE 4.2
Possible Ashfall Coverage from a Yellowstone Supereruption



SOURCE: Reproduced from Butler, *Environmental and Societal Impacts in New England Following a Potential Yellowstone Eruption*, p. 18. (We have modified the legends.)

NOTE: In the simulations, New England receives some ash fall. Data are from Mastin, Van Eaton, and Lowenstern, "Modeling Ash Fall Distribution from a Yellowstone Supereruption," p. 18.

[a] Butler, *Environmental and Societal Impacts in New England Following a Potential Yellowstone Eruption*, p. 18.

[19] Mastin, Van Eaton, and Lowenstern, "Modeling Ash Fall Distribution from a Yellowstone Supereruption."

skin.[20] Mass exposure to free crystalline silica could theoretically cause silicosis, which is currently a human-caused phenomenon stemming from unsafe work environments. Concentrations of ionic species, such as fluorine or magnesium, would increase in soil and water. Human and animal ingestion of these ionic species could cause health problems.[21]

Major volcanic ash clouds and cover would also affect land and sea transportation: Visibility would be reduced, and physical impediments would hamper driving along roads. Physical infrastructure, including buildings and telecommunication towers, is also likely to be damaged in areas with deep ashfall. Even on well-constructed buildings, roofs could collapse. In low-resource countries or areas without high construction standards and regulations, more-significant breakdown of structures would be anticipated if deeply buried in ash.[22]

Global, Longer-Term Effects

The global effects of supereruptions stem primarily from the release of sulfur in the form of volcanic gas (i.e., sulfur dioxide).[23] When inhaled, sulfur dioxide can cause breathing problems and can even be toxic. Sulfur dioxide combined with water in the air makes sulfuric acid, which can create acid rain and can harm plants and other living organisms. On a larger scale, an explosive supereruption injects volcanic ash and sulfur dioxide into both the troposphere and stratosphere, and the sulfur dioxide forms sulfuric acid aerosols. Both the ash and aerosols reflect incoming sunlight and create a cooling effect on Earth's surface. Because of the nature of the different atmospheric layers, the ash and aerosols will circulate for longer in the stratosphere. Although the ash typically remains in the stratosphere for months, sulfuric acid aerosols could remain for several years and circulate over an entire hemisphere or even globally.[24]

Table 4.3 shows the effects on the climate and estimated times of onset and duration. Some lasting effects of note are global cooling for up to three years, reduced tropical precipitation for about a year, reduction in precipitation from Asian and African monsoons for up to two years, and ozone depletion for up to two years.

The climate effects will have many tangible impacts to human life, as documented by Stephen Self.[25] Cooler temperatures; changes in rainfall amounts; and potentially short-term, local warm spells will affect agricultural yields. Regional changes in rainfall or precipitation from monsoons can result in either flooding or drought. The fine ash particles, sulfur oxides, and sulfuric acid in the lower atmosphere can cause respiratory health problems. Despite their shorter lifetimes in the lower atmosphere, these aerosols can reach hemispheric or global coverage. The aerosols can damage the engines and instruments of aircraft through chemical etching, and options for diversion of flight paths would be limited by the potentially global spread of aerosols. Ozone depletion would allow harmful UV B radiation—which is linked to higher risk of skin cancer and cataracts—to reach the ground in mid- to high-latitude regions. The aerosols and ash in the atmosphere could also disrupt communication infrastructure (e.g., satellite signals), inhibit relief efforts and cooperation, and negatively affect world financial markets.

[20] American Lung Association, "Volcanic Ash."

[21] Centers for Disease Control and Prevention, "Key Facts About Volcanic Eruptions."

[22] U.S. Geological Survey (USGS), "Volcano Hazards Program."

[23] Part of what makes a supervolcano explosive is a high concentration of volatile gases in the magma, which are released when the magma rises to the surface. Other releases include water and CO_2, but the amount released is not significant compared with what already exists in Earth's atmosphere (Self and Blake, "Consequences of Explosive Supereruptions").

[24] Center for Science Education, "How Volcanoes Influence Climate."

[25] Self, "Explosive Super-Eruptions and Potential Global Impacts."

TABLE 4.3
Large, Explosive Volcanic Eruptions' Effect on Climate

Effect	Begins After	Duration
Stratospheric warming	1–3 months	1–2 years
Global cooling	Immediate	1–3 years
Winter warming of Northern Hemisphere continents	0.5 to 1.5 years	1–2 winters
Reduced tropical precipitation	Immediate	~ 1 year
Reduction of Asian and African summer precipitation from monsoons	0.5 to 1 year	1–2 summers
Ozone depletion, enhanced UV radiation	1 day	1–2 years
Enhanced El Niño conditions	0.5 to 1 year	1–2 years

SOURCE: Features information from Robock and Outten, "Volcanoes."
NOTE: UV = ultraviolet.

A large modulating factor and source of uncertainty on the expected magnitude of the effect of aerosols is the amount of sulfur released by a supereruption.[26] The amount of sulfur released depends on where the supervolcano is and the sulfur content of the magma, which can be estimated around known sites but with great uncertainty. For a true supereruption, estimates for sulfur dioxide injected into the stratosphere have been made based on extrapolations from smaller eruptions and analysis of crystal inclusions of past super-eruption deposits, indicating a range of 10^{12} to 10^{13} kg of sulfur dioxide injected into the stratosphere.[27]

HTHH illustrated another modulating factor of eruption damage in that it is in an oceanic setting and exploded below the ocean surface. Its effects included tsunamis, global shock waves, contaminated water, and polluted air with ash over hundreds of kilometers, severed undersea cables that provided communications for Tonga, and created a plasma bubble that disrupted Global Positioning System (GPS) and communication satellites.[28] However, one significant effect from having erupted underwater is that HTHH shot water vapor into the stratosphere, increasing stratospheric water vapor content by 10 to 15 percent. Because water vapor is a GHG, some people are concerned that the potential increase in global temperature by 0.035°C in the following five years would push against climate change mitigation efforts.[29]

Another factor that determines the variety of expected effects of a supereruption is whether it occurs in an equatorial region or closer to the poles. The stratospheric aerosols for equatorial eruptions (e.g., Mount Pinatubo in 1991) will spread across the entire globe, although higher-latitude eruptions might only have stratospheric aerosols in the hemisphere of the eruption but could cause greater cooling.[30] On the latter, dif-

[26] In the case of the 1991 Mount Pinatubo eruption (VEI of 6), the aerosol cloud encircled Earth in less than two weeks and had spread across much of the globe within three months. It persisted in concentrations sufficient to influence Earth's radiation budget (that is, the amount of the sun's radiation that goes into Earth's atmosphere and how much is reradiated back out) for more than three years and induce global cooling of about 0.5°C for a year (Self and Blake, "Consequences of Explosive Supereruptions"). Contrast that with the 2022 eruption of the Hunga Tonga–Hunga Ha'apai volcano (HTHH) (VEI of 5.7) that released about 2 percent of the sulfur that Mount Pinatubo did (about 10^9 kg of sulfur dioxide) and might have cooled Earth by only 0.004°C (Bai et al., "Infrasound Waves and Sulfur Dioxide Emissions Caused by the 2022 Hunga Volcanic Eruption"; Besl, "Tonga Eruption May Temporarily Push Earth Closer to 1.5°C of Warming").

[27] Self, "Explosive Super-Eruptions and Potential Global Impacts."

[28] Shinbori et al., "Generation of Equatorial Plasma Bubble After the 2022 Tonga Volcanic Eruption."

[29] Besl, "Tonga Eruption May Temporarily Push Earth Closer to 1.5°C of Warming."

[30] Sjolte et al., "Major Differences in Regional Climate Impact Between High- and Low-Latitude Volcanic Eruptions"; Zhuo et al., "Climate Impact of Volcanic Eruptions."

ferent studies show uncertainty, and amounts of cooling might also depend on the season in which the eruption takes place.[31]

The latitude of the eruption also changes the resulting patterns in atmospheric circulation (i.e., the North Atlantic Oscillation), which can affect temperature changes in specific regions. This is important because, although the global cooling might be around 1 to 2°C, regional temperature changes could be ±4°C.[32] For instance, with an equatorial eruption, the U.S. East Coast and northern Europe might experience winter warming while southern Europe cools. For a northern, high-latitude eruption, there could be the opposite temperature effect in both winter and summer.[33] However, studies using both observations and models have shown that there is still uncertainty about the effect on atmospheric circulation, and further research is needed.[34]

What Are the Risks from Supervolcanoes?

The risk from a supervolcano stems from the likelihood of a supereruption occurring and the consequences of the eruption. In this and the next section, we discuss the likelihood of a supereruption and both the short-term and longer-term consequences from the different effect mechanisms resulting from a supereruption. For the consequences, we focus on the case of a continental supereruption (i.e., VEI of 8) as the likely worst case but also note differences if it were an oceanic supereruption. Throughout, we convey the quality of evidence to support our risk assessment and its associated confidence levels.

Effect estimates are based on the scale of disruption from supereruptions observed in the geologic record, combined with extrapolation of effects observed in smaller eruptions during historical times. Shorter-term risks depend heavily on the location of the supereruption. A supereruption's effect on humans, their economy, their quality of life, and their governments is very much likely to be a function of how close the erupting volcano is to major population centers and how much of the expected ashfall occurs on populated land versus ocean. However, supereruptions in sparsely populated areas or even oceanic areas will still be consequential to the environment and ecological stability: Such resources as fish, oceans, and rainwater could be highly negatively affected. Because the varied effects on different features of ecosystem stability, quality of life, and societal stability are likely so much larger and harder to characterize than the other types of hazards considered in this report, we consider the confidence in the estimates of effect intensity, duration, and geographic extent to be moderate. This uncertainty might also be relatively unimportant in that a supereruption's short-term local and regional effects likely pale in comparison to the longer-term risks posed by atmospheric and resulting climate changes. Because of these differences, we present short-term consequences separately from longer-term consequences.

What Is the Likelihood of a Supereruption?

There have been no supereruptions during recorded human history. The most recent supereruption identified was the Oruanui eruption of Taupō volcano in New Zealand 26,500 years ago. The most recent supereruption prior to that was the Toba eruption in Indonesia nearly 50,000 years earlier. Given this timescale,

[31] Paik et al., "Impact of Volcanic Eruptions on Extratropical Atmospheric Circulations"; Zhuo et al., "Climate Impact of Volcanic Eruptions."

[32] Sjolte et al., "Major Differences in Regional Climate Impact Between High- and Low-Latitude Volcanic Eruptions."

[33] Sjolte et al., "Major Differences in Regional Climate Impact Between High- and Low-Latitude Volcanic Eruptions."

[34] Paik et al., "Impact of Volcanic Eruptions on Extratropical Atmospheric Circulations."

the best estimate of the probability of a supereruption comes from estimates of the recurrence interval of past supereruptions. We show a range of these estimates in Table 4.4.

Recurrence intervals have been estimated from the geologic record of past eruptions using two techniques. The first is based on identifying and dating supereruption deposits in the rock record. Such estimates range from 714,000 to 17,000 years. The main reason for this wide range is differences in approaches to accounting for underreporting. The rock record is incomplete because deposits remain undiscovered or are destroyed. Models have been developed to account for this incompleteness; as this modeling has evolved, estimates of the recurrence interval have decreased over time, with the most recent estimate being the shortest at 17,000 years.

A second approach is based on the dates of sulfur horizons in ice cores. Volcanic eruptions emit substantial amounts of sulfur dioxide, and correlated sulfur layers of sufficient concentration detected in opposite hemispheres (Greenland and Antarctica) are used to identify the occurrence of eruptions with global sulfur deposition and to infer the volcanic radiative forcing caused by the eruption. Using this method, Jiamei Lin and her colleagues identified the Taupō supereruption and two other eruptions that occurred between 60,000 and 9,000 years ago and were larger than that at Taupō.[35] Although these two larger eruptions have not been identified in the geologic record, evidence of their existence from ice-core records shows three supereruptions during their study period, allowing them to compute a supereruption recurrence interval of 14,300 years.

The most-recent estimates from the rock and ice records are broadly similar, indicating that the best estimate for the recurrence interval for a supereruption is on the order of 15,000 years. This equates to an annual probability of a supereruption of 6.7×10^{-5}.

What Are the Effects of Continental Supervolcano Eruptions in the Short Term?

The short-term consequences of a supereruption are local to regional in scale and stem from pyroclastic flows and ashfall. The dynamic period of volcanic activity would last from days to weeks, although the effects on human functioning could last for years. Everything within a 100-km radius would be destroyed from pyroclastic flows, while ashfall would have smaller but substantial effects up to thousands of kilometers away. The magnitude of short-term effects will depend strongly on the location of the eruption, with greater effects in densely populated and heavily developed areas. It is therefore difficult to assess comprehensively the range

TABLE 4.4
Global Return Periods for Supereruption

Source	Return Period, in Years	Probability of Occurrence in the Next 100 Years, as a Percentage
Mason, Pyle, and Oppenheimer, "The Size and Frequency of the Largest Explosive Eruptions on Earth"	714,000 to 45,000	0.014 to 0.222
Loughlin et al., *Global Volcanic Hazards and Risk*	133,350[a]	0.075
Rougier et al., "The Global Magnitude–Frequency Relationship for Large Explosive Volcanic Eruptions"	17,000[b]	0.587[c]
Lin et al., "Magnitude, Frequency and Climate Forcing of Global Volcanism During the Last Glacial Period as Seen in Greenland and Antarctic Ice Cores"	14,300	0.697

[a] The uncertainty around the return period is 16,000.

[b] 95% confidence interval: 5,200 to 48,000.

[c] 95% confidence interval: 1.905 to 0.208.

[35] Lin et al., "Magnitude, Frequency and Climate Forcing of Global Volcanism During the Last Glacial Period as Seen in Greenland and Antarctic Ice Cores."

and magnitude of effects. However, in Table 4.5 and the discussion that follows, we have summarized the major effects in the four categories: mortality, ecosystem instability, societal instability, and reduced human capabilities.

Consequences: Mortality

Mortality as a direct effect of a continental supervolcano eruption would be the result primarily of pyroclastic flow, although deaths from buildings collapsing under the weight of accumulated ashfall is also likely. Pyroclastic flows would likely kill everyone within a roughly 100-km radius. The numbers of deaths would depend on population density at the eruption site, although a supereruption in any dense area could cause millions of deaths quite rapidly.

Consequences: Ecosystem Instability

In the short term, ashfall from a supereruption would be likely to affect agricultural production. According to the Food and Agriculture Organization of the United Nations,

> Ashfall can have serious detrimental effects on crops and livestock depending mainly on ash thickness, the type and growing conditions of the crop, the timing and intensity of subsequent rainfall, condition of pasture and animals prior to ashfall, and availability of uncontaminated feed and water.[36]

As a point of reference, the United States produces 28 percent of the world's soybeans and 32 percent of the world's corn.[37] Given the spatial distribution of U.S. production, perhaps 95 percent of U.S. soybean and corn farming could be lost to ashfall from a supereruption in the central United States.[38] This loss could span several seasons because agricultural recovery from ash burial would likely be a gradual process.

Animal deaths are also an expected consequence of a supereruption, although numbers vary depending on the location of the eruption. Terrestrially, such animals as livestock, birds, bugs, and bees would be killed

TABLE 4.5
The Short-Term Local and Regional Effects of a Supereruption

Consequence Category	Estimated Effect	Confidence in the Estimate
Mortality	• Tens of thousands to tens of millions	Moderate
Ecosystem instability	• Terrestrial- and marine-animal deaths • Agricultural production disrupted or halted • Water quality degraded	Moderate
Societal instability	• Tens of billions to more than 1 trillion U.S. dollars • Infrastructure destroyed (100-km radius) and degraded (up to thousands of kilometers away) • Significant reduction in regional to hemispheric air traffic and surface transportation (1,000-km radius) • Potential political instability	Low to moderate
Reduced human capabilities	• Degraded human health	Moderate

36 Food and Agriculture Organization of the United Nations, "Tonga Volcanic Eruption."

37 International Production Assessment Division, "Commodity Explorer."

38 International Production Assessment Division, "United States."

either by incineration from falling ash or by disease, famine, polluted water, or other secondary effects.[39] Because underwater explosions increase water temperature and acidify oceans, fish might die as they quickly swim upward, causing dissolution of gases in their bodies. Ash from eruptions gets stuck in gills and digestive tracts.[40] Ash could also introduce fluoride contamination that could sicken both humans and animals. Furthermore, acid rain kills vegetation and would be destructive to both agricultural crops and animals.

Consequences: Societal Instability

Arjun Mahalingam and his colleagues estimated around $1 trillion in losses from VEI 6 eruption scenarios in densely populated locations (Mount Merapi and Mount Rainier).[41] These estimates reflect values from direct property loss, business interruption, and follow-on losses in the value of investments.

Pyroclastic flows from a VEI 8 eruption would destroy all infrastructure in a 100-km radius from the eruption site, while infrastructure would be degraded up to thousands of kilometers out by ashfall. For example, roofs or entire buildings and electrical and telecommunication infrastructure can collapse from thick ash loads, and electrical, communication, water, and transportation equipment can be disabled or destroyed by fouling, corrosion, and overheating.[42]

A supereruption could have tremendous regional, hemispheric, or even global effects on aviation, depending on where the eruption was, for weeks or longer. In addition to disrupting travelers, this would lead to major losses in global aviation revenues. As discussed in the "Ashfall" section under "The Mechanisms of a Supervolcano Catastrophe" earlier in this chapter, the 2010 VEI 3 eruption of Eyjafjallajökull shut down aviation throughout much of Europe for days. A supereruption in Yellowstone, for example, would likely shut down more than 15,000 public- and private-use airports in the United States, plus military air bases.[43] Similarly, ash fallout could interrupt surface transportation within a 1,000-km radius. Combined, these effects on society could also result in political instability.

Consequences: Reduced Human Capabilities

The eruption of a supervolcano, including resulting ash, would certainly have an effect on human health. Respiratory distress and illnesses, including asthma, bronchitis, and chronic obstructive pulmonary disease, would be a major concern, particularly in people with asthma. Silicosis (a human-caused lung disease caused by inhalation of crystalline silica) could become a widespread problem in affected areas. High ash levels would also be expected to cause eye and skin irritation and exposure to fluorine-contaminated water.[44] In general, access to safe water would likely be highly problematic. These would also have significant effects on both behavioral and psychological health for humans on a regional to global scale.

What Are the Effects of Continental Supervolcano Eruptions in the Longer Term?

The longer-term consequences of a supereruption scale up to the hemispheric or global geographic extent and stem from sulfur-based stratospheric aerosols that can spend years in the stratosphere. In Table 4.6, we have summarized the major effects in the categories of mortality, ecosystem instability, societal instability, and reduced human capabilities, like we did with short-term consequences.

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[39] De Jong Boers, "Mount Tambora in 1815."

[40] Caballero et al., "Fish Mortality Associated to Volcanic Eruptions in the Canary Islands."

[41] Mahalingam et al., *Impacts of Severe Natural Catastrophes on Financial Markets*.

[42] Volcanic Ashfall Impacts Working Group, "Volcanic Ash and Gas Impacts and Mitigation."

[43] Bureau of Transportation Statistics, "Number of U.S. Airports."

[44] Hansell, Horwell, and Oppenheimer, "The Health Hazards of Volcanoes and Geothermal Areas."

TABLE 4.6
Summary of Longer-Term Supereruption Consequences from Stratospheric Aerosols

Consequence Category	Estimated Effect	Confidence in the Estimate
Mortality	Hundreds of millions to billions	Low: lack of peer-reviewed research
Ecosystem instability	Hemispheric to global destruction of ecosystem, with significant degradation of ecosystem function, lasting months to decades	Moderate: sparse peer-reviewed research
Societal instability	Hemispheric to global, causing hundreds of billions to tens of trillions of U.S. dollars in disruption of government functions, lasting months to decades	Low to moderate: inferred from sparse peer-reviewed research, lacking specific estimates
Reduced human capabilities	Hemispheric to global, causing significant diminishment of human capability, lasting years to decades	Moderate: inferred from sparse peer-reviewed research

Several factors contribute to the size of the range of estimates in Table 4.6, including ranges in sulfur levels at the site of the supervolcano, duration of the eruption, potential for a high-latitude supervolcano to affect only one hemisphere, and potential for mitigations to be enacted in the warning time leading up to the eruption (e.g., food storage and alternatives, refuges).

Consequences: Mortality

The expected mortality resulting from the longer-term atmospheric aerosols from a supereruption would be a range of billions to hundreds of millions of people, predominantly through the loss of food supply. This estimate has a low confidence level caused by a lack of peer-reviewed literature with rigorous supporting analysis: Most available numbers are speculative (e.g., news website quoting a scientist) and heuristics based on expected damage to agriculture.[45] One of the only supereruptions in human history, the Youngest Toba Tuff about 74,000 years ago, has been the subject of much scientific study to narrow down the uncertainty about its effects on the climate and potential role in slowing the evolution of human civilization.[46]

Consequences: Ecosystem Instability

Virtually all ecosystems are estimated to be either destroyed or significantly degraded because of regional changes in temperature, precipitation, and direct harm from ash and aerosols to plants and animals for a period of months to decades, depending on the intensity of the stratospheric aerosol effect. Claudia Timmreck and her colleagues' modeling of a range of sulfur emission levels shows that rainforest, trees, and the net primary productivity (i.e., the production of biomass that is associated more with human nutrition) could be reduced by 50 percent in the first two years, and some regions will experience increased fires after three years.[47] These estimates also show that the vegetation could take decades to recover. Some effects vary regionally, but the expected geographical spread would be on a hemispheric or global scale, depending on the latitude of the eruption. Additional uncertainty in this estimate comes from other modulating factors—the natural climate variability (e.g., El Niño–Southern Oscillation [ENSO]) or the length of the eruption being assumed to be ten days but could be on the order of 100 days—and other research limitations: not being able to model the combined effects of ash and stratospheric aerosols or not using an Earth-system model that fully models atmospheric chemistry.

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[45] On heuristics, see, for example, Denkenberger and Blair, "Interventions That May Prevent or Mollify Supervolcanic Eruptions"; and Oppenheimer, "Limited Global Change Due to the Largest Known Quaternary Eruption, Toba ≈74 kyr BP?"

[46] Timmreck et al., "Climate Response to the Toba Super-Eruption."

[47] Timmreck et al., "Climate Response to the Toba Super-Eruption."

Consequences: Societal Instability

On societal stability, research literature mentions the likely effects on the agricultural industry and government functions but without much supporting analysis.[48] Because the range of levels of potential sulfur content released in a supereruption is so wide, there is a lack of direct calculation on duration or extent of the shutdown of air traffic, agricultural production, and trade disruptions. Rough estimates are based on the size of the agricultural industry or aviation industry and are typically in a range between hundreds of billions of dollars and tens of trillions of dollars in economic disruption, although estimates conflate effects from volcanic ash and sulfur aerosols.

Consequences: Reduced Human Capabilities

Quality of life or human capability is generally estimated to diminish significantly for years to decades based on the mortality and ecosystem effects. On top of negative effects on human health and nutrition, communications and mobility could be limited.[49] Like the shorter-term effects, this will yield immense negative effects on global human behavioral and psychological health.

Notable Differences for Submarine Eruptions

Most submarine volcanism produces nonexplosive lava flows that pose no risk to humans. Some, however, particularly along convergent plate margins, such as in the western Pacific, can be violently explosive. Although few examples exist, shallow submarine explosive eruptions can produce ash columns and sulfur emissions reaching the stratosphere, tsunamis, and high-energy pyroclastic flows. An example is the VEI 5–6 eruption of HTHH in 2022. This was among the largest volcanic eruptions recorded with modern instrumentation and the largest since the 1991 Mount Pinatubo eruption.[50] It sent an ash column 58 km high and launched underwater pyroclastic flows that traveled 80 to 100 km at speeds of up to 100 km per hour.[51] It also created tsunamis that spanned the Pacific Ocean.[52] Although casualties were minor, several fatalities were attributed to tsunamis, some as far away as Peru.[53]

Overlying ocean's effect on eruption behavior is not well understood, but the water can influence the eruption and effects. HTHH is very shallow, with the caldera floor being perhaps 150 m below the sea surface when it erupted in 2022.[54] In addition to creating pervasive tsunamis, the water can react explosively with the magma, creating an extremely loud event (the HTHH eruption was heard as far away as Alaska).[55] In addition, although the amount of sulfur the eruption produced was unexceptional, the eruption set a record for the greatest amount of water injected into the atmosphere since satellite measurements have been available.[56]

[48] See, for example, Self, "Explosive Super-Eruptions and Potential Global Impacts."

[49] Self, "Explosive Super-Eruptions and Potential Global Impacts"; Timmreck et al., "Climate Response to the Toba Super-Eruption."

[50] Poli and Shapiro, "Rapid Characterization of Large Volcanic Eruptions."

[51] Doman and Palmer, "The 'Mind-Blowing' Sea Floor Changes Caused by Tongan Volcanic Eruption."

[52] Yuen et al., "Under the Surface."

[53] "Two People Drowned by Abnormally High Waves in Peru After Tonga Volcano."

[54] Doman and Palmer, "The 'Mind-Blowing' Sea Floor Changes Caused by Tongan Volcanic Eruption."

[55] Yuen et al., "Under the Surface."

[56] Millán et al., "The Hunga Tonga-Hunga Ha'apai Hydration of the Stratosphere." The amount of water that entered the atmosphere was more than 28.4 billion gallons, equivalent to 58,000 Olympic swimming pools (Patel, "Tonga Volcano Blasted Unprecedented Amount of Water into Atmosphere").

A result of this massive addition of water is that the eruption affected global climate temporarily not by cooling from sulfate aerosols but rather by warming from the greenhouse effect of water vapor.[57]

A shallow submarine supereruption could thus have effects like those of an eruption on land, including pyroclastic flows that could run up onto nearby shores and ashfalls. If there are populated areas nearby, the damage could be like that of a land-based eruption. If the large amount of water added to the atmosphere in the HTHH eruption is typical of shallow submarine eruptions, it could mitigate the effect of sulfur in affecting the climate, possibly decreasing the long-term global effects. Water depth's effect on the impact of submarine eruptions is unknown, but effect presumably decreases with increasing depth, such that supereruptions in deeper water would have lesser effects.

How Will the Risk from Supervolcanoes Change in the Next Decade?

In the next decade, it is unlikely that the risk from a supervolcano eruption will change. The inherent geological properties are such that there will continue to be a very low probability of another supereruption in the near future. Although there has been some public debate about the planet being due for a supervolcano eruption, scientists have refuted these claims. There is media speculation about scenarios in which humans might be motivated to trigger a supereruption either intentionally or unintentionally,[58] but there is still much uncertainty and lack of understanding in the exact mechanisms for those scenarios. Any change in the risk within the ten-year time frame would be due to an invigorated investment in risk management efforts—in particular, additional geological research to better constrain probability and characteristics of the potential supervolcano and atmospheric modeling to better understand the possible global consequences and improved monitoring and forecasting for volcanoes to better support evacuation and regional preparation. In the next section, we summarize the risk management options.

What Has Been and Could Be Done to Manage Risk from Supervolcanoes?

Table 4.7 describes four mitigation dimensions—reducing the likelihood of occurrence, disrupting the mechanisms that lead to the risk, reducing the severity of effects, and enhancing response and recovery—and provides mitigation options for each dimension.

In the rest of this section, we address two general strategies for paths to mitigation, reducing the probability or severity of supereruptions or reducing their consequences.

Reduce the Probability or Severity of Supereruptions

Some have proposed engineering approaches for preventing, delaying, or reducing the intensity of volcanic eruptions. These proposals include various approaches to draining heat from the magma chamber, reducing the confining pressure to release magma nonexplosively, and increasing the confining pressure on the magma chamber roof to prevent brittle failure.[59] All these proposals are purely speculative and have no cred-

[57] Khaykin et al., "Global Perturbation of Stratospheric Water and Aerosol Burden by Hunga Eruption."

[58] See, for example, Wilcox et al., "Defending Human Civilization from Supervolcanic Eruptions."

[59] Denkenberger and Blair, "Interventions That May Prevent or Mollify Supervolcanic Eruptions"; Wilcox et al., "Defending Human Civilization from Supervolcanic Eruptions."

TABLE 4.7
Supervolcanoes: Overview of Risk Mitigation Opportunities

Mitigation Dimension	Mitigation Approach
Reduce the likelihood of occurrence.	• Highly speculative options have been proposed, but no credible options are known.
Disrupt the mechanisms leading to risk.	• Highly speculative options have been proposed, but no credible options are known.
Reduce the severity of effects.	• Issue warnings and conduct large-scale evacuations. • Exercise one or more theoretical, untested geoengineering options, such as containing erupted material with stratospheric tents or sky bots[a] and injecting greenhouse agents into the stratosphere.
Enhance response and recovery.	• Provide for disaster recovery, population evacuations, and developing replacement resources to sustain populations. • Coordinate and communicate observations and warnings.

ible basis for expecting useful results. Each would involve immense amounts of capital, time, and public will. Any attempt at implementing any of them would likely not begin for at least 50 to 100 years.

Reduce the Consequences of Supereruptions

Another approach to reducing risk is to reduce the consequences of a supereruption. Here again, several approaches have been proposed, including evacuating people prior to eruption, containing or diverting erupted material, active solar radiation management to counter the cooling effects of stratospheric sulfur, and improving human survivability posteruption.[60] Most of these approaches are also highly speculative, complex, and resource intensive.

Evacuation, however, is a proven risk-reduction measure that has reaped enormous benefits in past eruptions.[61] For example, 85,000 people were evacuated in the weeks prior to the 1991 Mount Pinatubo eruption, saving an estimated 10,000 to 20,000 lives. Similarly, nearly 400,000 people were evacuated prior to the 2010 eruption of Merapi in Indonesia, again saving an estimated 10,000 to 20,000 lives.[62] The key to successful evacuation is an understanding of the signals that indicate a pending eruption and sufficient monitoring capacity to detect those signals. This monitoring applies both to known volcanoes and globally for new, previously unknown volcanic activity.[63] Known signs of a pending eruption include ground displacement, increased seismic activity, changes in the amount and content of gas emissions, changes in groundwater levels, and changes in gravity around the site that enable imaging and a better understanding of movement below ground.[64] Despite the general association of these indicators with volcanic eruption, they are not always present before an eruption, nor do they always lead to an eruption. In addition, these indicators can

[60] Denkenberger and Blair, "Interventions That May Prevent or Mollify Supervolcanic Eruptions"; Loughlin et al., *Global Volcanic Hazards and Risks*; Pham et al., "Nutrition in Abrupt Sunlight Reduction Scenarios"; Winstead and Jacobson, "Forest Resource Availability After Nuclear War or Other Sun-Blocking Catastrophes"; Xu et al., "Possible Mitigation of Global Cooling Due to Supervolcanic Eruption via Intentional Release of Fluorinated Gases."

[61] Loughlin et al., *Global Volcanic Hazards and Risk*; Self, "Explosive Super-Eruptions and Potential Global Impacts."

[62] Loughlin et al., *Global Volcanic Hazards and Risk*.

[63] Volcano observatories are specific to each country. For example, USGS partners with state organizations in the United States. There are some international efforts to improve the availability of remote sensing data (i.e., satellite observations) for volcano monitoring, such as European Volcano Observatory Space Services and the Committee on Earth Observation Satellites' disaster risk management volcano pilot project.

[64] Self, "Explosive Super-Eruptions and Potential Global Impacts."

provide weeks' to years' advance notice of a supereruption.[65] Combined, these uncertainties make knowing when scientists and authorities should call for evacuation difficult. Accurate forecasting of the size and timing of impending volcanic eruptions leading to timely evacuation remains a primary goal of most volcanology research, but it is still unreliable, particularly for explosive eruptions.[66] Furthermore, because of the multitude of factors and uncertainties in the precise estimate of an individual supereruption, ranking and prioritizing the known volcanic sites based on overall risk are difficult.

To enable improvements in monitoring, evacuation, and other supereruption mitigation, many areas could be further researched. This includes further geologic study to characterize the past record of supervolcanoes, sophisticated modeling of ash and atmospheric aerosol effects to better understand expected effects on the biosphere and climate, and additional economic analysis to better constrain estimates of the cascading effects of the short- and longer-term hazards. The organizations likeliest to coordinate or provide governance over these efforts would be the Volcano Disaster Assistance Program (which aims to reduce volcanic risk in developing countries with significant risk) or one of the partners that fund it (USGS and the U.S. Agency for International Development Office of U.S. Foreign Disaster Assistance).

Summary

A supereruption from a supervolcano would primarily damage and destroy the natural environment and create instability in ecosystems. This would first occur at a regional scale immediately after the supereruption with pyroclastic flow and ashfall effects and continue for weeks. At a larger, potentially global scale, the effects of stratospheric aerosols can persist for years. The estimated lower bound for the return period of a supereruption is 15,000 years, and the risk of supervolcano hazards is expected to remain constant in the near future. It is possible to predict a supereruption weeks or years in advance, which allows the most-promising mitigation of supereruption consequences through effective monitoring and subsequent warning and evacuation. Given the potential extent of the needed evacuation, the efforts would not be trivial and face significant challenges.

Several factors create large variability in potential supereruption effects. The latitude of the supervolcano, the sulfur content of the volcanic gases, and potentially the depth under water can all affect the geographical extent and magnitude of the atmospheric aerosol effects. The proximity to populated regions and the eruption onset speed and duration affect what would be exposed and the effectiveness of evacuation efforts.

Although a robust body of scientific evidence supports a risk assessment of supervolcanoes, some knowledge gaps remain that would improve understanding of the risk and bolster risk mitigation efforts.

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65 Gualda and Sutton, "The Year Leading to a Supereruption."

66 Loughlin et al., *Global Volcanic Hazards and Risk*.

CHAPTER 5

Asteroid or Comet Impact: Summary of Risk

An asteroid's orbit intersecting with Earth's creates the potential for a collision that can cause a far-reaching blast wave, thermal pulse, ejecta, and other devastating effects.[1] Comets likewise pose a threat, although they are generally larger than most asteroids and tend to have orbits that make timely detection more diffi-

TABLE 5.1

Asteroid or Comet Impact: Overview of Risk

Risk Dimension	Assessment for Asteroid or Comet Impact
Most-significant consequences	• Primary – Widespread physical destruction caused by blast wave and thermal pulse – For objects large enough to reach the ground mostly intact, cratering, generation of hot ejecta, injection of debris into the atmosphere, and potential triggering of earthquakes, volcanic activity, or tsunamis, with potential global range in case of large impactors • Secondary – Societal instability – For large impactors, damage to the global ecosystem, with potential extinction of humans and many other species
Factors that influence the magnitude of risk	• Size and composition of the impactor (smaller objects are likelier but cause less damage; metal-core asteroids cause more damage than similarly sized rocky objects) • Location of impact for small to medium-sized impactors • Warning time (longer warning time increases mitigation options) • Available planetary defense capabilities
Likelihood of risk	• Small impactors (~30 m diameter, city-sized devastation): every ~100 years • Medium impactors (~300 m diameter, country-sized devastation): every ~100,000 years • Large impactors (~3,000 m diameter, global devastation): every ~10 million years • The risk of a comet impact is less than 1% of the risk of an asteroid impact.
Temporal nature of the risk and change in the next decade	• Smaller impactors can hit without—or with only a few days or hours of—warning. • Asteroids in certain orbits, and many comets, are likely to be detected only a few months to a few years before impact, likely providing insufficient time for a mitigation campaign. • For larger asteroids, a warning time of many years or decades can be expected. • Longer warning times, when combined with advances in spaceflight technologies, will enable in-space mitigation and more-extensive preparations on the ground. • Asteroid detection and tracking capabilities have improved significantly in the past two decades and will improve even further in the next decade, thus increasing warning. • However, the risk from comets has remained—and will remain—relatively constant.
Quality of the evidence supporting the assessment	• Geologic record of major impacts; astronomical observations of near-Earth asteroids and comets; and planetary defense technology demonstrations, such as NASA's DART mission

NOTE: DART = double asteroid redirection test; NASA = National Aeronautics and Space Administration.

[1] Schmidt, *Planetary Defense*.

cult while leading to higher-impact energies in the case of a collision.[2] Table 5.1 summarizes the related risk dimensions. The rest of this chapter discusses these dimensions in more detail.

When a large asteroid or a comet collides with Earth, as has happened multiple times over the course of Earth's history, the impact releases an amount of energy many times that of all the world's nuclear weapons combined, which thus causes massive damage to Earth's ecosystem and leads to the extinction of many species.[3] For example, approximately 66 million years ago, an asteroid of approximately 10 km diameter impacted near the Gulf of Mexico and ended the age of the dinosaurs.[4] Smaller objects hit much more frequently but also cause less damage. For example, in 2013, a space rock of approximately 18 m diameter entered the atmosphere over the Siberian city of Chelyabinsk and disintegrated at approximately 30 km altitude. The resulting blast wave injured more than 1,000 people and broke windows throughout the city.[5] The impact of a large asteroid or comet can be considered the largest risk to human civilization—and human existence—of all astrophysical threats.[6]

Preventing major asteroid and comet impacts, and thus protecting humanity from the potential extinction that such impacts could cause, has become possible in recent decades thanks to advances in both astronomy and spaceflight capabilities.[7] Even if an impact cannot be prevented, especially in the case of a smaller impactor, it might be possible to protect populations and resources in the affected area given enough warning time.[8] This chapter provides an overview of the risk that asteroid and comet impacts pose and what can be done to mitigate it.

What Is Known About the Causes of Risk from Asteroid and Comet Impacts?

The solar system contains not only the sun, the planets, and their moons but also billions of smaller objects, ranging in mass from pebbles to continent-sized rocks. Many of these objects orbit the sun in the asteroid belt between Mars and Jupiter, far away from Earth, or even farther away in the Oort cloud, well beyond the orbit of Pluto. However, some have orbits that intersect Earth's, creating the potential for a collision that could be devastating if an object larger than approximately 50 m in diameter is involved.[9]

In addition to asteroids, comets pose a threat. Although the overall likelihood of a comet impact is estimated to be less than 1 percent of that of an asteroid impact, comets tend to be larger and faster, but at the same time harder to detect in time, because of their different orbits.[10]

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[2] Boe et al., "The Orbit and Size–Frequency Distribution of Long Period Comets Observed by Pan-STARRS1"; Kelvey, "The Comet Conundrum"; Near-Earth Object Science Definition Team, *Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs*.

[3] Committee to Review Near-Earth-Object Surveys and Hazard Mitigation Strategies Space Studies Board, *Defending Planet Earth*.

[4] Lunar and Planetary Institute, "Global Effects."

[5] Popova et al., "Chelyabinsk Airburst, Damage Assessment, Meteorite Recovery, and Characterization."

[6] Burns and Parsons, "Astrophysical Existential Threats."

[7] NASA, "Planetary Defense."

[8] Center for Near Earth Object Studies, "2022 Interagency Tabletop Exercise."

[9] NASA, "Planetary Defense."

[10] Kelvey, "The Comet Conundrum."

Luckily, major impacts are exceedingly rare. Objects large enough to cause major damage on the ground, comparable to that caused by the blast of a large nuclear weapon, hit Earth on average once per century. Larger objects can be expected to hit much less frequently (once every tens of thousands to hundreds of millions of years) but can destroy whole countries—or even most life on Earth, as was the case of the aforementioned dinosaur killer that impacted approximately 66 million years ago (described further in the next section).[11]

Most very large asteroids (greater than approximately 1 km in diameter) that could collide with Earth have been detected in the past several decades, and none of them poses a risk in the foreseeable future (a century or more).[12] However, new, potentially hazardous asteroids that are smaller but still dangerous are detected several times per year, so it is conceivable that, at some point in the next several decades, one will be discovered that poses a significant impact risk.[13]

The population of comets crossing Earth's orbit is less well characterized, so comet impacts are more unpredictable.[14]

Once a new potentially hazardous asteroid or comet is discovered, it usually takes several days to several months before astronomers can determine its orbit with sufficient certainty to assess the likelihood of a collision. In some cases, however, global observation campaigns spanning several years are required, and the predicted likelihood of collision can be refined only gradually. Even once it is determined that an impact is certain, predicting the exact impact location on Earth will take additional time and is sometimes possible only a few days or weeks prior to impact—an important consideration for terrestrial emergency managers.[15]

What Are the Risks from Asteroid and Comet Impacts?

The effects of an asteroid or comet impact are generally well known: a powerful blast wave and thermal pulse, and—in case of objects large enough to reach the ground mostly intact—cratering; generation of hot ejecta; injection of debris into the atmosphere; and potential triggering of earthquakes, volcanic activity, or tsunamis. Even small impactors set free energies comparable to that of a very large nuclear weapon: the equivalent of approximately 10 megatons (Mt) of TNT for an object 50 m in diameter.[16] Objects of more than approximately 140 m in diameter can also cause global effects, ranging from triggering slight changes in worldwide climate to wiping out most life on Earth. The magnitude of these effects depends greatly on the size and composition of the impactor, which are generally not precisely known until a few days or even hours prior to impact—unless there is enough warning time (many years) to send a deep-space reconnaissance mission to the object while it is still far from Earth.

Figure 5.1 shows the likelihood of an impact and Figure 5.2 the expected global fatalities, by object size. Figure 5.3 summarizes the key risk factors (likelihood, effects, and uncertainty) for asteroid impacts.

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[11] Committee to Review Near-Earth-Object Surveys and Hazard Mitigation Strategies Space Studies Board, *Defending Planet Earth*.

[12] Center for Near Earth Object Studies, "2022 Interagency Tabletop Exercise"; Center for Near Earth Object Studies, "Sentry."

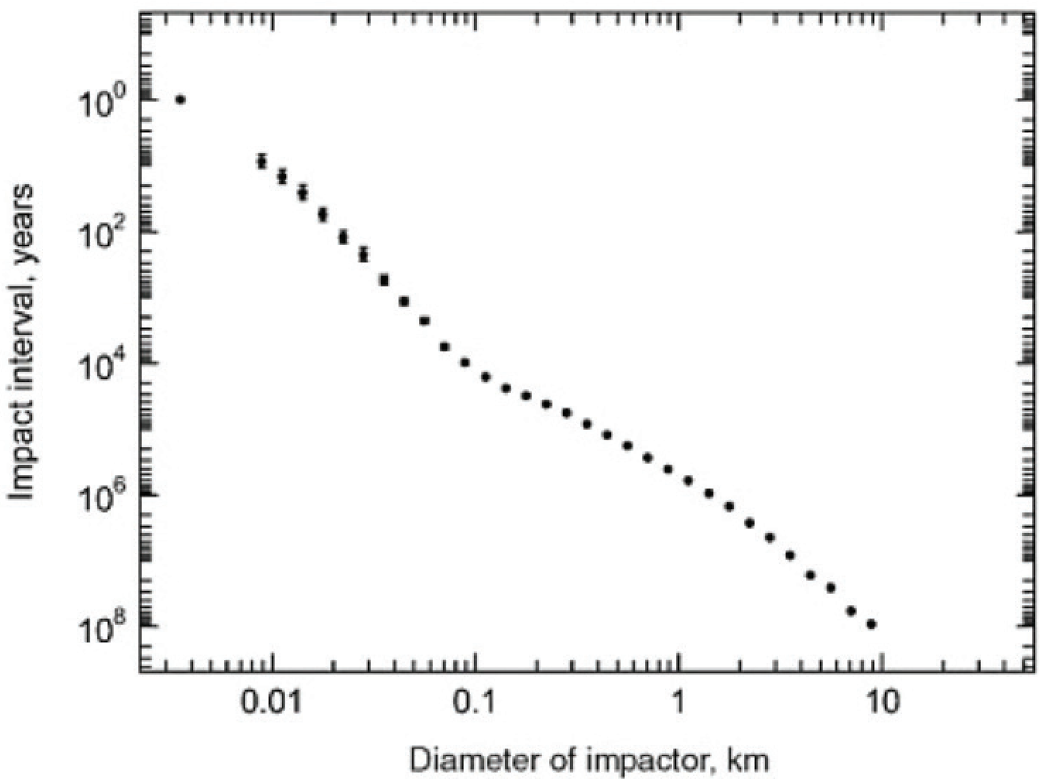
[13] Center for Near Earth Object Studies, "2022 Interagency Tabletop Exercise."

[14] Kelvey, "The Comet Conundrum."

[15] Note that, in contrast with the likelihood and location of an impact, the date of a potential impact can generally be predicted relatively early after discovery.

[16] Note that, although impact energies and some impact effects (blast wave, thermal pulse, and cratering) can be compared with that of nuclear weapons, an asteroid or comet impact does not cause an electromagnetic pulse or generate radioactivity or radioactive fallout (unless it destroys nuclear infrastructure, such as a nuclear power plant).

FIGURE 5.1
Likelihood of Asteroid or Comet Impact, Depending on Object Size



SOURCE: Reproduced from Committee to Review Near-Earth-Object Surveys and Hazard Mitigation Strategies Space Studies Board, *Defending Planet Earth*, p. 8. Used with permission of National Academies Press; permission conveyed through Copyright Clearance Center, Inc.

NOTE: The following note appears with the original: "Current estimates of the average interval in years between collisions with Earth of near-Earth objects of various sizes, from about 3 meters to 9 kilometers in diameter. The uncertainty varies from point to point, but in each case is on the order of a factor of two; there is also a strong correlation of the values from point to point. SOURCE: Courtesy of Alan W. Harris, Space Science Institute."

Consequences: Mortality

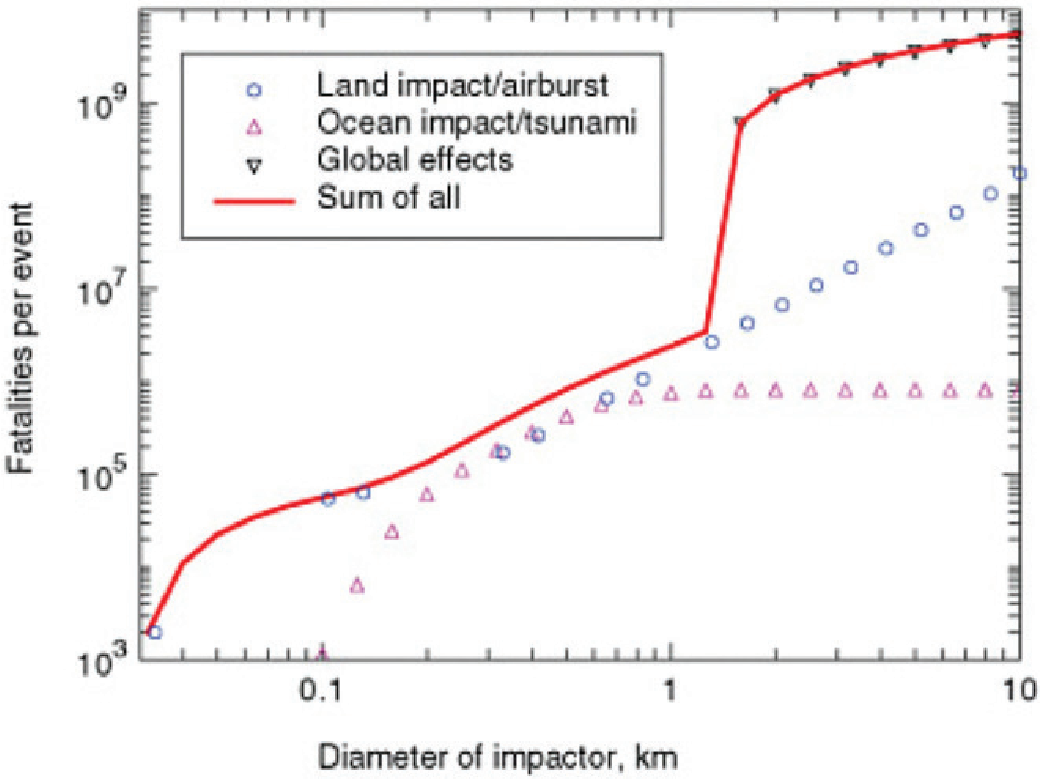
Direct fatalities from an asteroid or comet impact are caused by cratering, the blast wave, the thermal pulse, and falling ejecta, as well as by secondary effects, such as fire, earthquake, or tsunami triggered by an impact.[17] Disruption of health care services will cause additional fatalities for people who were initially only injured. Impact injuries—including those leading to death—include blunt and penetrating trauma, burns, smoke inhalation, and suffocation. The number of injured and dead depends mostly on the following factors:

- the amount and distribution of energy released by the impact, which, in turn, is tied to the object's mass, size, speed, impact angle, shape, and composition
- the location of the impact, which determines the population density in the affected area, as well as cratering dynamics and amount and type of ejecta (with the greatest difference being between land and ocean impacts)

[17] Committee to Review Near-Earth-Object Surveys and Hazard Mitigation Strategies Space Studies Board, *Defending Planet Earth*.

FIGURE 5.2

Expected Fatalities from Asteroid or Comet Impact, Depending on Object Size



SOURCE: Reproduced from Committee to Review Near-Earth-Object Surveys and Hazard Mitigation Strategies Space Studies Board, *Defending Planet Earth*, p. 22. Used with permission of National Academies Press; permission conveyed through Copyright Clearance Center, Inc.

NOTE: The following note appears with the original: "Model of fatalities per event for impacts of various size NEOs. The solid curve represents the total fatalities associated with both ocean and land impacts, including those with global effects. The sharp increase in the solid (red) curve reflects the assumption of a large increase in fatalities for an impact that crosses the global-effect threshold. SOURCE: Courtesy of Alan W. Harris, Space Science Institute."

- the protective measures, such as sheltering or evacuation, that the affected population took prior to impact
- the resilience of the affected population in dealing with the physical and psychological trauma of such a destructive event.

Depending on the impact energy, direct effects can cause casualties up to a few kilometers from the impact site for smaller objects or up to thousands of kilometers for larger ones.[18] However, for larger impactors (beyond a few hundred meters in diameter), global effects, such as soot injection into the atmosphere—both directly from impact ejecta and from firestorms triggered by the thermal pulse and the spread of hot ejecta—and resulting changes in climate that last for years, if not centuries, can cause casualties beyond those from direct effects.[19] A more detailed discussion of global effects is provided in the next section.

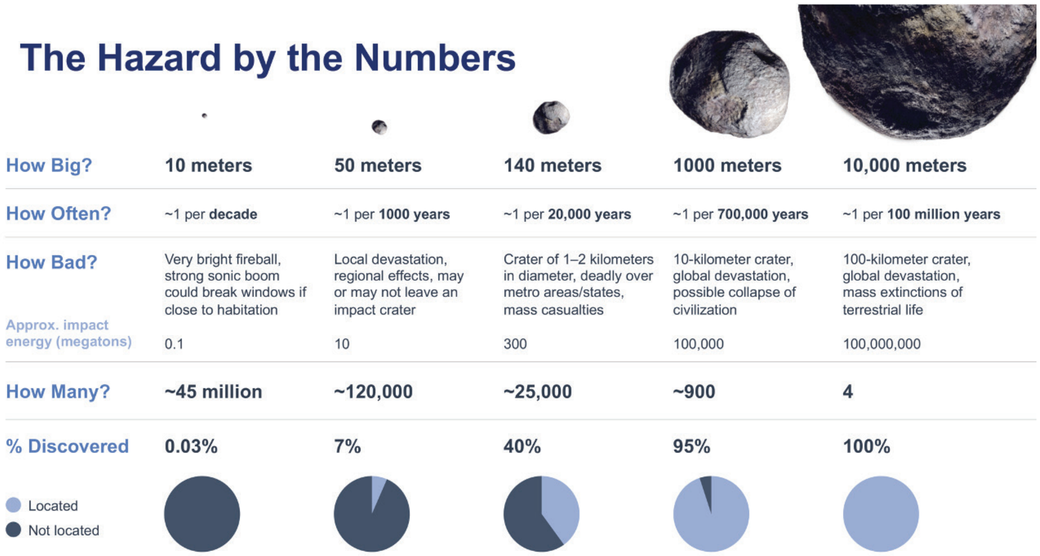
Figure 5.4 shows the probability distributions of how many people would be affected (including injured and dead) by the impact of two hypothetical asteroids. The left figure is for an impactor with a diameter

[18] Center for Near Earth Object Studies, "2022 Interagency Tabletop Exercise."

[19] Morgan et al., "The Chicxulub Impact and Its Environmental Consequences."

FIGURE 5.3

Key Factors Influencing the Risks of Asteroid Impact

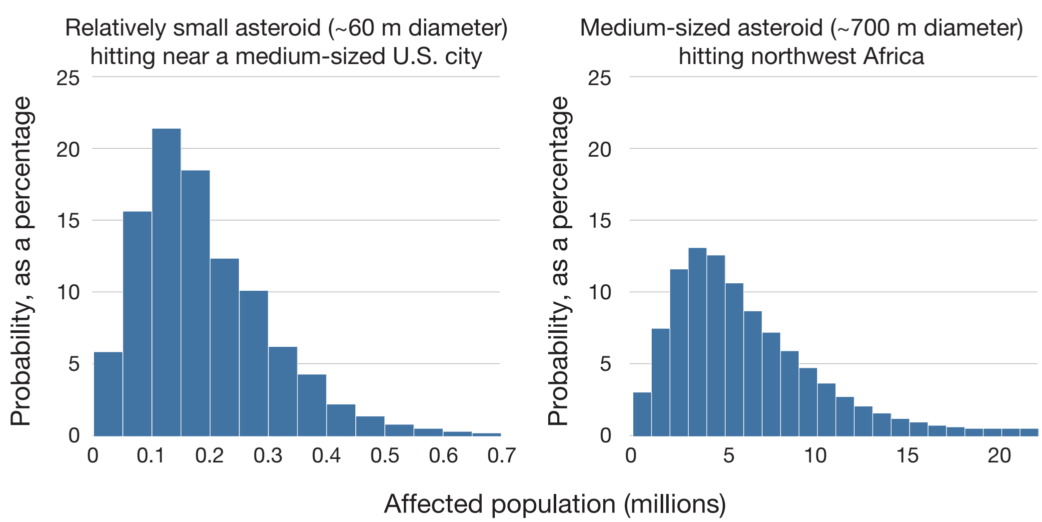


SOURCE: Reproduced from Johns Hopkins University Applied Physics Laboratory, *Day 1*, p. 42. Courtesy NASA/JPL-Caltech.

NOTE: Objects below a few hundred meters in diameter are unlikely to present an existential risk as defined in Chapter 1. All numerical values shown are rough estimates. The "How Many?" row indicates the number of asteroids.

FIGURE 5.4

Estimated Numbers of People Directly Affected by Two Asteroid Impact Scenarios



SOURCES: Adapted from Johns Hopkins University Applied Physics Laboratory, *Module 3*, p. 14 (left); and Wheeler et al., "Probabilistic Asteroid Impact Risk Assessment," p. 3 (right).

NOTE: The hypothetical asteroid on the left is approximately 60 m in diameter and hypothetically hits near a medium-sized U.S. city. The hypothetical asteroid on the right is approximately 700 m in diameter and hypothetically hits in northwest Africa. The shape of the distribution of the estimated number of people affected is caused by uncertainties in asteroid size, composition, and exact impact location; accuracy limitations of blast and thermal modeling and casualty simulation tools; and similar factors. This would affect casualty estimates for a real-world impact scenario as well.

between 60 m and 80 m, resulting in an energy release comparable to that of an 11-Mt nuclear blast, near a medium-sized U.S. city. As is evident, even such a relatively small impactor is likely to kill tens of thousands of people. The right figure is for an object in the 700-m size range impacting in the northwestern part of Africa. Immediate casualties for this scenario range in the millions, with more to be expected from cascading hazards.

An asteroid or comet at the upper end of the size spectrum, such as the Chicxulub impactor, which was approximately 10 km in diameter and wiped out the dinosaurs and many other species, would similarly lead to human extinction if no preparatory measures are taken well ahead of impact.[20]

Consequences: Ecosystem Instability

As shown in Figure 5.3, a small to medium-sized impactor (between tens and hundreds of meters in diameter) would physically destroy an area the size of a small city to the size of a small country. This would, of course, affect the environment and ecosystems in this area, but at least the direct effects are not expected to pose a catastrophic or existential risk to humanity. However, impacts of objects larger than approximately 1 km in diameter would cause global effects through injection of debris into the atmosphere, large-scale spread of hot impact ejecta and resulting firestorms, and triggering earthquakes and tsunamis—and potentially volcanic eruptions—as well as other cascading effects worldwide.[21] This would unbalance ecosystems for many years, which could lead to the extinction of many species—including *Homo sapiens*.

Consequences: Societal Instability

Economic and Infrastructure Disruption

Even relatively small objects, such as the one mentioned previously, can destroy a city-sized area and most of its infrastructure, including offices and industrial facilities. Figure 5.5 illustrates how much critical infrastructure a small (roughly 60 m in diameter) asteroid impacting a U.S. city would destroy or disrupt. Along with the hundreds of thousands of casualties expected in such a scenario, likely mental health impact on even more people, and the movements of displaced populations in the aftermath, this would have a direct and significant impact on a region's or country's economic activity.

However, only impacts of much larger objects (1 km in diameter and above), which happen very rarely (as shown in Figure 5.3), can directly trigger truly catastrophic or existential economic and infrastructure disruptions.

Governance Disruption

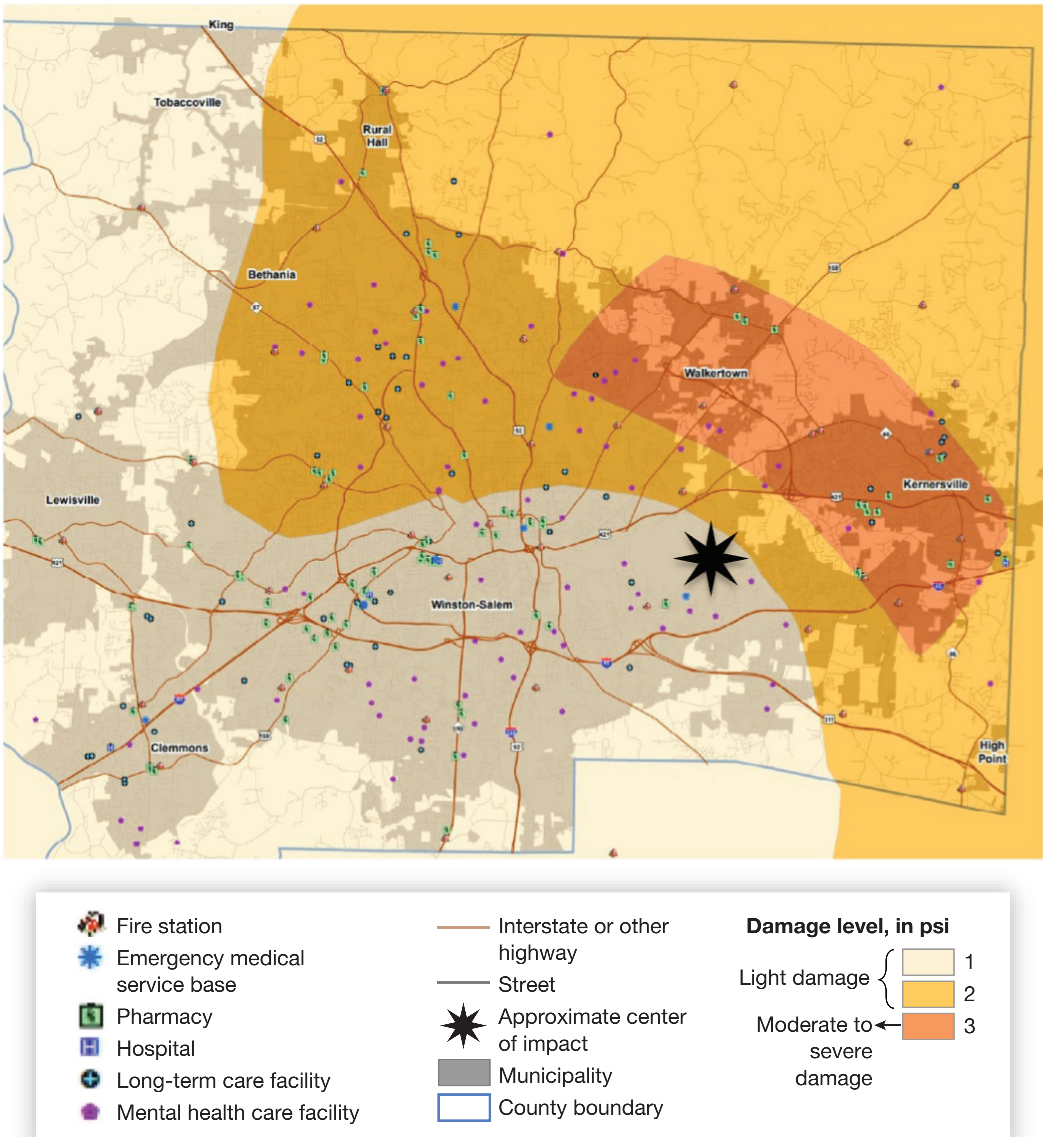
Like with other critical infrastructure, an impactor can destroy or degrade government facilities and kill, injure, or displace government personnel in the area covered by its blast and other direct effects. This would reduce local governance capacity in the affected area and thus make immediate emergency response, as well as longer-term recovery, more challenging. However, unless the impact takes place directly over a capital, most national governance capacity can be expected to survive the immediate aftermath. National governance can nevertheless be disrupted or at least strained by subsequent indirect effects, especially in the case of a major impact that affects long-term economic development, food security, law and order, national security, and other areas.

[20] Lunar and Planetary Institute, "Global Effects."

[21] Schulte et al., "The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous–Paleogene Boundary"; Titus et al., "A Review of Common Natural Disasters as Analogs for Asteroid Impact Effects and Cascading Hazards."

FIGURE 5.5

Select Critical Infrastructure That Would Hypothetically Be Directly Affected by the Hypothetical Impact of a Relatively Small Asteroid on a Medium-Sized U.S. City



SOURCE: Reproduced from Johns Hopkins University Applied Physics Laboratory, *Module 4*, p. 9. Courtesy NASA/JPL-Caltech. (We have adapted the legend.)

NOTE: psi = pound per square inch. The hypothetical asteroid in this example measures approximately 60 m in diameter. The burst height is approximately 13 km. The irregularity of the shapes of the damage areas are due to the way an object's energy is released during the impact process.

Uncertainty and Timing of Risk from Asteroid and Comet Impacts

As mentioned earlier, many of the most-dangerous asteroids have already been detected and a collision with Earth ruled out for the foreseeable future. However, smaller objects, of which many are still undiscovered, can cause significant damage as well. Comets, on the other hand, even though they are generally larger than most asteroids, are likelier to go undetected until a few years—or even just a few months—prior to impact because their orbits differ from those of typical asteroids.[22]

At the same time, once an impact is likely or certain, the location and extent of damage are more challenging to predict because of uncertainty about the object's exact size, composition, and trajectory.[23] Thus, there is both aleatory uncertainty (an impactor could be discovered at any time) and epistemic uncertainty (there generally is not enough information available, particularly early on, to precisely predict the effects of a likely impactor) involved. To reduce both kinds of uncertainty, planetary defense efforts involve improving both detection and characterization capabilities. Furthermore, if a potential impactor is detected early enough (many years prior to impact), a mitigation mission could be launched that would nudge the threatening object into a new trajectory that does not intersect with Earth or that would disintegrate the object into smaller pieces that would cause less combined damage than one large impactor might.

Timelines involved can range from zero notice to decades or even centuries of warning. For example, there was no warning of the relatively small object that entered Earth's atmosphere over the Siberian town of Chelyabinsk in February 2013, so the local population was surprised by the blast wave, which caused windows to break throughout the city and injured more than 1,000 people.[24] On the other hand, the trajectory of a known and well-characterized object, such as the asteroid Apophis, can be predicted tens, if not hundreds, of years into the future, so there would be decades of time to prevent—or at least prepare for—an impact from an object like that. Table 5.2 illustrates these timelines and associated options.

How Will the Risk from Asteroid and Comet Impacts Change in the Next Decade?

The risk of a yet-undiscovered object impacting Earth with little or no warning time can be reduced by increased detection efforts for such objects. The risk of an object, once discovered to be on an impact course, actually causing significant damage can be reduced by preparing the capabilities needed to rapidly characterize (i.e., find out more about an object's exact trajectory, size, shape, and composition) and potentially mitigate it (i.e., destroy it or change its trajectory so it no longer impacts Earth). Terrestrial preparedness plays a role as well in minimizing the damage in case an impact is unavoidable.

Thanks to substantial efforts by the global planetary defense community in these areas since the early 1990s, the risk from asteroid impacts has gone down and will continue to do so in the foreseeable future. However, it is hard to quantify this reduction because the number of still-undetected potentially hazardous objects is unknown. In addition, most current planetary defense efforts focus on asteroids so—because of the aforementioned different characteristics of comets—are less effective at reducing the risk of comet impacts.[25]

What is clear, though, is that this reduction was made possible by relatively recent advancements in spaceflight technologies and space observation capabilities, so continuing investments in those fields will also help protect humans—and potentially all life on Earth—from extinction. This includes the development of very large, low-cost, responsive launch vehicles, such as SpaceX's Starship (in testing at the time of this writing in early 2024) and Blue Origin's New Glenn launcher (being designed at the time of this writing). It also includes political and diplomatic efforts aimed at creating and supporting organizations focusing on planetary defense, such as NASA's Planetary Defense Coordination Office (PDCO), and at facilitating the devel-

[22] Kelvey, "The Comet Conundrum."

[23] Baum, "Uncertain Human Consequences in Asteroid Risk Analysis and the Global Catastrophe Threshold."

[24] Popova et al., "Chelyabinsk Airburst, Damage Assessment, Meteorite Recovery, and Characterization."

[25] Kelvey, "The Comet Conundrum."

TABLE 5.2
Warning and Response Time Horizons for Asteroid and Comet Impacts

Warning Time Before Impact	Initial Discovery	Terrestrial Response Type[a]	Example Scenario
None	• Direct observation • Bolide detection sensors	Comparable to earthquake response (essentially no notice)	Chelyabinsk, 2013[b]
Minutes	• Radar[c]	Comparable to earthquake response	
Hours	• Radar[c] • Telescopes	Comparable to tornado response (half an hour or so of warning)	Sudan, 2008 (2008 TC3)[b]
Days	• Radar[c] • Telescopes	Comparable to hurricane response (a couple of days of warning)	
Weeks	• Radar[c] • Telescopes	Customized rapid response	NASA/FEMA TTX1 in 2013
Months	• Telescopes	Customized rapid response	2021 PDC NASA/FEMA TTX4 in 2022
Years	• Telescopes	Customized long-lead response	NASA/FEMA TTX2 in 2014 NASA/FEMA TTX3 in 2016 2015 PDC 2019 PDC
Decade+	• Telescopes	Customized long-lead response	99942 Apophis[b] 2023 DW[b] 2013 PDC 2017 PDC 2023 PDC

SOURCES: Features information from Chesley, Chodas, and Yeomans, "Asteroid 2008 TC3 Strikes Earth"; Giorgini et al., "99942 Apophis"; Popova et al., "Chelyabinsk Airburst, Damage Assessment, Meteorite Recovery, and Characterization"; and the TTXs and PDC at Center for Near Earth Object Studies, "Hypothetical Impact Scenarios."

NOTE: TTX = tabletop exercise. TC_3, 99942 Apophis, and 2023 DW are actual minor-planet designations for these objects. YYYY PDC is a minor-planet designation for a hypothetical asteroid in a hypothetical scenario in an exercise held in the year noted (YYYY).

[a] The nature of response would be on a timeline and face challenges similar to the named hazards because of the similar warning times in the "Warning Time Before Impact" column.

[b] Actual asteroid.

[c] Only if radar happens to be covering the right area.

opment and testing of relevant in-space mitigation technologies, such as nuclear explosive devices.[26] Because planetary defense is a long-term effort—after all, the likelihood of a major impact during any given decade or even century is very low—it also requires long-term societal support.

In the next section, we discuss in more detail what has been done in this context so far and what could be done in the future.

[26] Although nuclear explosive devices are the most effective mitigation approach for most planetary defense scenarios, considerable legal and diplomatic complexities are involved in developing, testing, and employing nuclear explosive devices for planetary defense missions (see e.g., Osburg et al., *Nuclear Devices for Planetary Defense*).

What Has Been and Could Be Done to Manage Risk from Asteroid and Comet Impacts?

Mitigating the risk of devastating asteroid or comet impacts involves activities along a logic chain leading from initial discovery to dealing with the aftermath of an impact (Figure 5.6). At each stage, measures can be taken that reduce the associated risk. The available risk management options for each of the elements of the logic chain are presented in Table 5.3 and discussed in the text that follows. Only in the past few decades have humans' technological capabilities reached a point at which protecting Earth from asteroid and comet impacts has become feasible.

The need to defend Earth against asteroid and comet impacts was first seriously discussed in the early 1990s, which led to a congressional mandate to NASA to discover potentially hazardous asteroids over 1 km in diameter.[27] This mandate was then expanded to also include asteroids larger than 140 m.[28] These efforts were accompanied and informed by activities of academia and the international community, with exercises and conferences focusing on the topic taking place since the mid-2000s and two global working groups

FIGURE 5.6
Logic Chain for Planetary Defense

	Detection and tracking	Characterization and tracking	Mitigation	Terrestrial preparation
Informs	• Impact likelihood • Characterization • Assessment • Mitigation • Terrestrial preparation	• Impact likelihood • Impact location • Impact effects • Mitigation requirements and options • Terrestrial preparation requirements and options	• Terrestrial preparation	
Required contributing capability	• Telescopes in space and on Earth • Observer networks	• Telescopes • Radar • Deep-space missions	• Deep-space missions • Nuclear explosive devices • ICBMs	• Emergency alerting • Safeguarding critical infrastructure • Scalable response forces • Sheltering • Evacuation • Resilience

NOTE: ICBM = intercontinental ballistic missile. Some of these processes can and should occur in parallel (e.g., in-space mitigation and terrestrial preparation) or are iterative (e.g., characterization).

[27] Morrison, *The Spaceguard Survey*; Planetary Defense Interagency Working Group, *National Preparedness Strategy and Action Plan for Near-Earth Object Hazards and Planetary Defense*.

[28] Gregersen, "Planetary Defense"; Planetary Defense Interagency Working Group, *National Preparedness Strategy and Action Plan for Near-Earth Object Hazards and Planetary Defense*; Public Law 109-155, National Aeronautics and Space Administration Authorization Act of 2005.

TABLE 5.3
Asteroid or Comet Impact: Overview of Risk Mitigation Opportunities

Mitigation Dimension	Mitigation Option
Reduce the likelihood of occurrence.	• Try one or more experimental approaches of in-space deflection or disruption of threatening objects enabled by early detection of impactors.
Disrupt the mechanisms leading to risk.	• Try one or more experimental approaches of in-space deflection or disruption of threatening objects enabled by early detection of impactors.
Reduce the severity of effects.	• Try one or more experimental approaches of in-space disruption of impactors, large-scale evacuations, timely public warning, and increasing human civilization's resilience.
Enhance response and recovery.	• Coordinate planetary defense efforts. • Prepare terrestrial responses (e.g., evacuations). • Increase human civilization's resilience.

accredited by the United Nations being established in 2014.[29] These organizations also address relevant legal challenges.[30]

The creation of the PDCO in 2016 further accelerated related efforts.[31] Today, the United States continues to be the world leader on planetary defense, and—in close collaboration with global partners, such as the European Space Agency (ESA)—has established and demonstrated significant related capabilities:[32]

- in the 1980s, building the first telescope dedicated to discovering and tracking near-Earth objects (NEOs)
- in 1985, conducting the first space probe fly-by of a comet (Halley)
- in 2001, launching the first asteroid orbiter and lander (Near Earth Asteroid Rendezvous [NEAR])
- in the early 2000s, creating the first NEO impact–monitoring system (Sentry)
- in 2005, launching the first comet impact mission (Deep Impact)
- in 2006, completing the first comet sample return mission (Stardust)
- in 2023, completing the first asteroid sample return mission (Origins, Spectral Interpretation, Resource Identification, and Security—Regolith Explorer [OSIRIS-REx]).

Figure 5.7 provides an overview of these milestones and related events. Although many efforts are already underway and more are being discussed,[33] each of the mitigation activity types described in this section could benefit from additional attention—and funding—to reduce the remaining risk to humans more rapidly.

[29] International Academy of Astronautics, "IAA Planetary Defense Conference 2023"; PDCO, *Planetary Defense Interagency Tabletop Exercise 4*; Secure World Foundation, *Near-Earth Objects*; Office for Outer Space Affairs, *Near-Earth Objects and Planetary Defence*.

[30] Ad-Hoc Working Group on Legal Issues, *Planetary Defence Legal Overview and Assessment*.

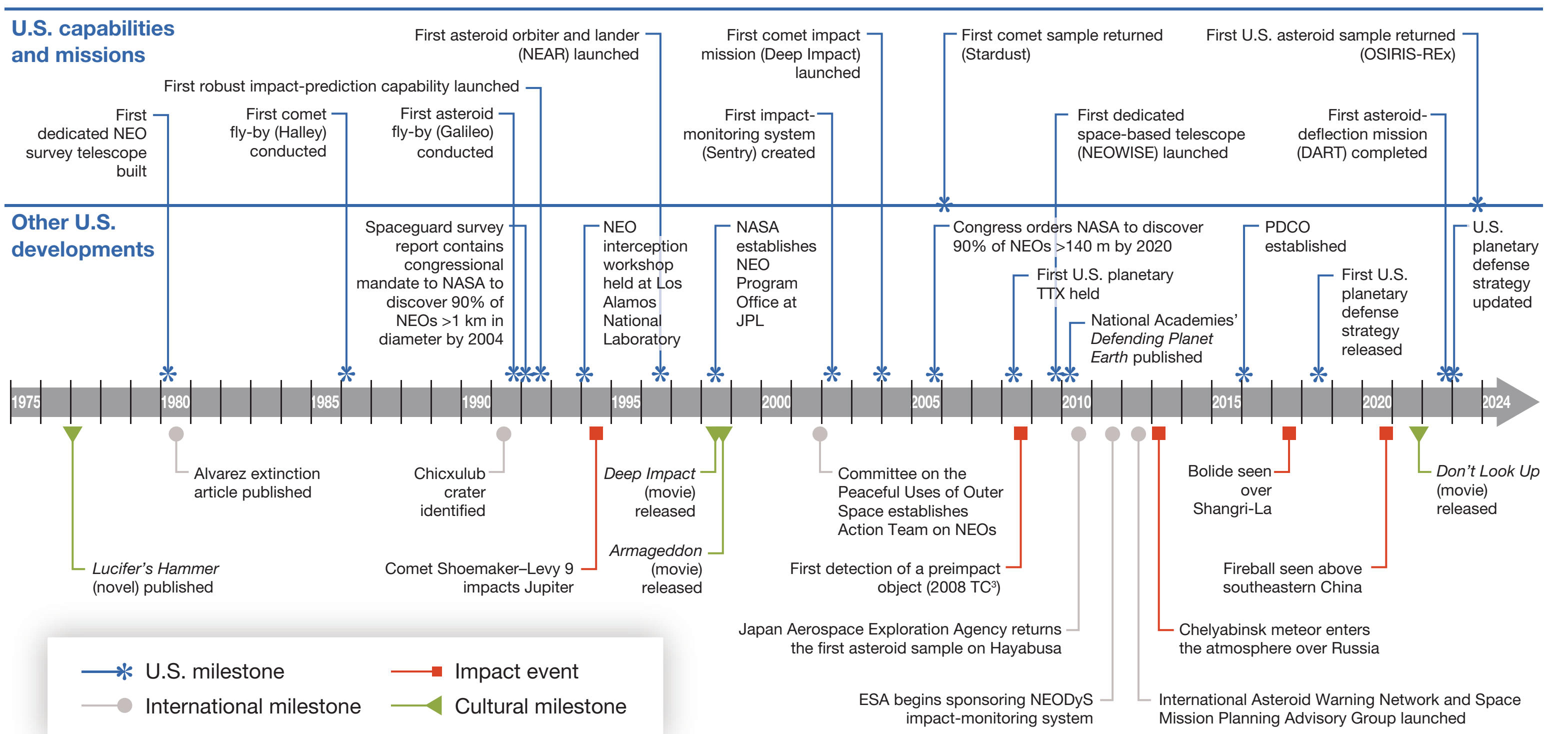
[31] Landis and Johnson, "Advances in Planetary Defense in the United States"; NASA, "Planetary Defense."

[32] Conway, Yeomans, and Rosenburg, *A History of Near-Earth Objects Research*; Near-Earth Objects Coordination Centre, "Risk List"; NASA, "Planetary Defense"; Planetary Defense Interagency Working Group, *National Preparedness Strategy and Action Plan for Near-Earth Object Hazards and Planetary Defense*.

[33] See, for example, Planetary Defense Strategy and Action Plan Working Group, *NASA Planetary Defense Strategy and Action Plan*.

FIGURE 5.7

Global Planetary Defense Milestones Since the 1980s



SOURCES: Alvarez et al., "Extraterrestrial Cause for the Cretaceous-Tertiary Extinction"; Committee to Review Near-Earth-Object Surveys and Hazard Mitigation Strategies Space Studies Board, *Defending Planet Earth*; Interagency Working Group for Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects, *National Near-Earth Object Preparedness Strategy and Action Plan*; Morrison, *The Spaceguard Survey*; Niven and Pournelle, *Lucifer's Hammer*; Planetary Defense Interagency Working Group, *National Preparedness Strategy and Action Plan for Near-Earth Object Hazards and Planetary Defense*; Planetary Defense Strategy and Action Plan Working Group, *NASA Planetary Defense Strategy and Action Plan*; Public Law 109-155, National Aeronautics and Space Administration Authorization Act of 2005.

NOTE: JPL = Jet Propulsion Laboratory; NEODyS = Near Earth Objects Dynamic Site.

Detection and Tracking

Mitigating the risk of catastrophic asteroid and comet impacts starts with detecting potentially hazardous objects, then tracking their positions over time, which allows calculation of their trajectories and, in turn, estimation of the risk of their impact with Earth. The more time there is between detection of an object and its impact, the higher the likelihood that mitigation measures, such as deflecting the object in deep space, will be successful.

Thus, constantly surveying the whole sky for new threats, then quickly determining their trajectories, is critical. Since the mid-1990s, NASA, ESA, and other organizations have built a substantial observation infrastructure for these purposes, consisting of both terrestrial and space-based telescopes. Related data-handling, processing, and analysis capabilities have been established as well.[34] However, many potentially hazardous objects—especially those less than 1 km in diameter—still remain undiscovered.

Characterization and Assessment

Once a potentially hazardous object is detected, assessing the likelihood and severity of a potential impact requires determining the object's orbit precisely and finding out more about its size, composition, and structure. This requires multiple observations from ground- and space-based telescopes, as well as planetary radars, which generally takes at least several weeks, if not months or years. It also greatly benefits from deep-space characterization missions conducted by reconnaissance spacecraft that fly by or orbit the object, or, ideally, land on it to gather this information and radio it back to Earth.

As an object approaches Earth, it becomes easier to determine its properties but—should it be on a collision course—harder to prevent it from hitting Earth.

As with detection efforts, NASA and other space agencies have developed and demonstrated the ability to conduct in-space characterization and assessments of asteroids and comets since the early 2000s, and additional missions are being planned.

In-Space Mitigation

Once it has been determined that an object is on a collision course with Earth, a deep-space mission can be launched to change the object's course (deflected) or to break it up into smaller, less dangerous parts (disrupted). However, this takes time—at the time of this writing, up to several years to design the mission, build the spacecraft, launch it, and have it fly toward its destination. Because a single mission can fail, redundancy through launching multiple missions increases the overall likelihood of success. Thus, time plays a critical role: If an object is detected less than several years before impact, launching a mitigation mission might not be possible. Warning time, of course, also affects the amount of terrestrial preparation that can be accomplished.

The following approaches to deflecting a threatening object are generally considered the most technologically mature:[35]

- The **kinetic impactor** mitigation approach involves sending one or more spacecraft on a course that has the spacecraft collide with the threatening object in deep space. The impact imparts a force on the object that changes its trajectory. However, because the mass of even a heavy spacecraft that can be

[34] Center for Near Earth Object Studies, "NEO Earth Close Approaches"; Near-Earth Objects Coordination Centre, "Risk List."

[35] Committee to Review Near-Earth-Object Surveys and Hazard Mitigation Strategies Space Studies Board, *Defending Planet Earth*.

launched with today's technology is small compared with the mass of even a small asteroid, the trajectory change will be small as well. Thus, this must be done many years before an impact so that even a small change leads to the object missing Earth. This is the only mitigation approach that has been tested so far, by NASA's DART mission in 2022.[36]

- With the **nuclear explosive device** approach, a spacecraft carrying a nuclear warhead is sent to rendezvous with the threatening object, and the nuclear device is then detonated a short distance (a few hundred meters) from the object's surface. The energy released by the nuclear reaction leads to some of the object evaporating suddenly, with the resulting force nudging the object into a new orbit.[37] Like with kinetic impact, the earlier this is done, the smaller the required trajectory change is. However, because of the large amounts of energy released during a nuclear detonation, this approach can impart larger trajectory changes on an object than a kinetic impactor spacecraft of equal mass can. Furthermore, this is the only mitigation approach that can also be used for disruption.
- The **gravity tractor** approach is suitable for mitigation missions with very long warning times (decades). For this, the mitigation spacecraft flies next to the threatening object for extended periods of time, kept in position by its own thrusters. The gravitational attraction between the spacecraft and the object imparts a slight change on the object's trajectory.
- For the **ion beam** mitigation approach, a spacecraft equipped with a powerful ion beam generator, such as an electric space propulsion engine, keeps station near the threatening object, aiming the ion beam at it to impart a small force. This can change the trajectory of an object over the course of many years.

In addition to these mitigation activities that take place in deep space, there has also been initial research on mitigation options near Earth in recent years, in case a—generally preferable—deep-space mitigation attempt fails.[38]

Because the ability to rapidly launch relatively large spacecraft is important for all mitigation approaches, the future availability of launch vehicles with large payload capacities that can be built relatively quickly and launched on short notice would increase the likelihood of successful characterization and mitigation missions.

Terrestrial Preparation

Even with sufficient warning time, mitigation missions can fail, so terrestrial preparations play an important role in risk mitigation. Depending on how much time is available, this could include warning the public, generating response capabilities and capacity to deal with the aftermath of an impact, and evacuation of the potential impact area. However, the uncertainty involved in predicting the exact impact location of a threatening object—even if it is certain to impact Earth somewhere—until shortly before an impact (hours, days, or weeks), in addition to the large-scale devastation that would exceed the capacity of traditional emergency responses, makes preparations challenging. Thus, improvements in object characterization and impact effect modeling can help improve terrestrial preparedness as well.

In recent years, China has started building planetary defense capabilities and announcing ambitious related plans. Although, in the event of an actual planetary defense emergency, being able to draw on the resources and capabilities of as many countries as possible is generally considered advantageous, such emer-

[36] NASA, "Double Asteroid Redirection Test."

[37] Burkey et al., "X-Ray Energy Deposition Model for Simulating Asteroid Response to a Nuclear Planetary Defense Mitigation Mission."

[38] See, for example, Lubin and Cohen, "Asteroid Interception and Disruption for Terminal Planetary Defense."

gencies are rare. On the other hand, in times with no impact hazard, building planetary defense capabilities and conducting successful planetary defense missions affect a country's global standing and can be leveraged for diplomatic and political—and potentially military—purposes.

Tables 5.4 through 5.6 describe how the mitigation and response measures discussed here fit into the warning time horizons outlined in Table 5.2.

Summary

Asteroids and comets can impact Earth and cause substantial damage, including the extinction of humans and many other species. The threat from asteroids and comets spans the geographic extent of consequences:

- A small asteroid, around 30 m in diameter and expected to impact roughly every 100 years, can destroy a city-sized area.
- A medium-sized asteroid, several hundred meters in diameter and estimated to hit every several hundred thousand years, can wipe out a country.
- An impact by a large asteroid (a few kilometers in size) or a comet would have global effects but is estimated to happen at most once every ten million years.

The population of large asteroids has been characterized quite comprehensively in the past several decades, so few unknowns remain. A substantial number of medium-sized and particularly small asteroids have not yet been discovered, though, which introduces considerable uncertainty. As mentioned previously, although comets are generally rarer than large asteroids, their orbits and other characteristics make them harder to discover and, in the long term, their trajectories harder to predict, so the uncertainty is greatest for them.

Mitigating this risk requires early detection of potentially threatening asteroids and comets and the ability to launch deep-space deflection missions on potentially very short notice. It also requires terrestrial preparedness. In the past several decades, the United States and its partners have made substantial progress particularly in asteroid detection, thus reducing the related risk.

TABLE 5.4
Characterization Options for Asteroid and Comet Impacts Based on Time Horizons

		Characterization Option		
Warning Time Before Impact	Type of Decisionmaking	Radar	Telescopes	Space Mission
No notice	Reactive only	—	—	—
Minutes	Comparable to nuclear attack response	—	—	—
Hours	Limited, high priority only	x[a]	x[a]	—
Days	Limited	x	x	—
Weeks	Deliberate but accelerated	x	x	—
Months	Deliberate	x	x	—
Years	Deliberate	x	x	x
Decade or more	Deliberate	x	x	x

[a] This option might not be viable for this amount of warning time.

TABLE 5.5

Mitigation Options for Asteroid and Comet Impacts Based on Time Horizons

		Mitigation Option				
Warning Time Before Impact	**Type of Decisionmaking**	**ICBM**	**Nuclear Explosive Device**	**Kinetic Impactor**	**Gravity Tractor**	**Ion Beam**
No notice	Reactive only	—	—	—	—	—
Minutes	Comparable to nuclear attack response	—	—	—	—	—
Hours	Limited, high priority only	Disruption[a]	—	—	—	—
Days	Limited	Disruption[a]	—	—	—	—
Weeks	Deliberate but accelerated	Disruption	Disruption[a]	—	—	—
Months	Deliberate	Disruption	Disruption, deflection[a]	—	—	—
Years	Deliberate	—	Disruption, deflection	Deflection[a]	—	—
Decade or more	Deliberate	—	Disruption, deflection	Deflection	Deflection	Deflection

[a] This option might not be viable for this amount of warning time.

TABLE 5.6

Terrestrial Response Options for Asteroid and Comet Impacts Based on Time Horizons

Warning Time Before Impact	Type of Decisionmaking	Terrestrial Response Option: General	Evacuation	Responders	Moves	Relocation	Shelter
No notice	Reactive only	—	—	—	—	—	—
Minutes	Comparable to nuclear attack response	• Isolate the power grid.[a] • Shut down nuclear reactors.[a]	—	—	—	—	—
Hours	Limited, high priority only	• Stop trains and road traffic.[a] • Shelter in place.[a]	• Order self-evacuations.	• Activate local emergency responders.	—	—	—
Days	Limited		• Organize evacuations.	• Stage regional responders and supplies.	—	—	—
Weeks	Deliberate but accelerated		• Execute comprehensive evacuations.	• Stage national and global responders and supplies.	• Make some permanent moves.	—	—
Months	Deliberate				• Make more-comprehensive permanent moves.	• Relocate certain industries, institutions, and resources.	• Build large, improvised shelters.
Years	Deliberate					• Potentially permanently relocate most populations, industries, institutions, and resources (depending on the deflection outcome).	• Establish long-term shelters deep underground.
Decade or more	—					• Potentially permanently relocate all populations, industries, institutions, and resources (depending on the deflection outcome).	• Establish off-Earth colonies.[a]

[a] This option might not be viable for this amount of warning time.

CHAPTER 6

Severe Pandemics: Summary of Risk

A pandemic is a "an epidemic occurring worldwide or over a very wide area, crossing international boundaries, and usually affecting a large number of people."[1] The decision to designate a public health event as a pandemic relates to the severity and spread of the disease over a wide area. Pandemics can be triggered by naturally occurring events or can be engineered using synthetic biology.

Throughout human history, pandemics have been a risk to human existence. Experts have warned with increasing concern about the growing risk of pandemics, yet the emergence of severe acute respiratory syndrome (SARS) coronavirus 2 (SARS-CoV-2), the virus that causes coronavirus disease 2019 (COVID-19), brought a renewed global awareness of the threats associated with pandemics. In its October 2022 *National Biodefense Strategy and Implementation Plan*, the Biden administration stated, "Biological threats—whether naturally occurring, accidental, or deliberate in origin—are among the most serious threats facing the

TABLE 6.1

Pandemic: Overview of Risk

Risk Dimension	Assessment for Pandemic
Most-significant consequences	• The most-significant risk comes from mortality and morbidity associated with pandemics, including excess deaths that result from such factors as an overburdened health care system. • Secondary risks result from "economic and social disruption on a massive scale."[a]
Factors that influence the magnitude of risk	• The single most important factor that influences the magnitude of the risk is human behavior, which has increased the chances of a naturally occurring or accidentally or deliberately caused pandemic. • Such factors as virulence and transmissibility of the pathogen and actions taken to prevent, mitigate, and respond to pandemics are also imperative for understanding the overall pandemic risk.
Likelihood of risk	• The human behaviors cited previously increase the likelihood of a pandemic. • However, scientific discoveries and technology development increase humans' understanding of infectious disease and the capacity for managing pandemics, which could serve to lower the severity of the risk.
Temporal nature of the risk and change in the next decade	• The risk of pandemics—whether naturally occurring or accidentally or deliberately caused—continues to increase because of human activity; however, naturally occurring pandemics remain the most-significant threat in the next decade. • As better understanding of the relationship between genome sequences and observed characteristics of a pathogen increases, the risk of a deliberate pandemic continues to increase.
Quality of the evidence supporting the assessment	• Strong evidence exists to conclude that the frequency of naturally occurring pandemics is likely to increase. • However, little evidence exists for assessing the risk of a pandemic resulting from a laboratory accident or a deliberately engineered pathogen.

[a] White House, *National Biodefense Strategy and Implementation Plan*, p. 2.

[1] "Pandemic."

United States and the international community."[2] These biological risks—including pandemics, such as the COVID-19 pandemic—can cause "death, hospitalizations, disabilities, psychological trauma, and economic and social disruption on a massive scale."[3] The *National Biodefense Strategy and Implementation Plan* also highlights that these risks are increasing because of human activity.[4]

In designating a disease outbreak as a pandemic, the World Health Organization (WHO) has established an alert system that ranges from phase 1 (predominantly animal infections but few human infections) to phase 6 (a pandemic with widespread human infection)."[5] Early stages of the WHO alert system involve disease spread in animals with the potential for spillover to humans, followed by an early spillover from animals to humans, with perhaps even small clusters of disease in humans. Phases 4 to 6 indicate a disease transmitted from human to human and that has outbreaks at the community level, with the higher-numbered phases indicating the greater severity and spread of the disease.[6]

What Is the Risk from Pandemics?

Pandemics have been a risk to human existence throughout history. The Black Death in the 14th century "killed 30 to 50 percent of the entire population of Europe."[7] The 1918 influenza caused 50 million, possibly 100 million, deaths across the globe.[8] In a 2006 Centers for Disease Control and Prevention workshop on the lessons of the 1918–1919 influenza pandemic, the significant human toll was recounted in detail from the physical to the psychological experience.[9]

In its September 2021 *American Pandemic Preparedness: Transforming Our Capabilities*, the Biden administration summarized the pandemic threat in the preceding 100 years as follows: "Since the early 1900s, there have been at least 11 serious viral outbreaks, caused by pandemic pathogens which span five virus families."[10] Most of these 11 outbreaks involved viruses that would be considered a risk for causing a pandemic.

In describing the potential magnitude of the biological threat, one account states,

> In total, there are ~1,400 known species of human pathogens (including viruses, bacteria, fungi, protozoa and helminths), and although this may seem like a large number, human pathogens account for much less than 1% of the total number of microbial species on the planet. . . . This means that the fraction of microbial diversity that we have sampled to date is effectively zero . . . .[11]

Pathogens have evolved over 3 billion years to have characteristics that can interact with a host, either for mutualistic survival (the benefit of the pathogen and the host) or for the sole benefit of the pathogen, which

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[2] White House, *National Biodefense Strategy and Implementation Plan*, p. 2.

[3] White House, *National Biodefense Strategy and Implementation Plan*, p. 2.

[4] White House, *National Biodefense Strategy and Implementation Plan*.

[5] Global Influenza Programme, *Pandemic Influenza Preparedness and Response*, pp. 24–26. The guidance also includes postpeak (possibility of recurrent events) and postpandemic (seasonal disease activity) periods beyond phase 6.

[6] Global Influenza Programme, *Pandemic Influenza Preparedness and Response*.

[7] Shipman, "The Bright Side of the Black Death."

[8] Oak Ridge Institute for Science and Education, *Workshop Proceeding*; Weintraub, "As COVID Turns 3, Experts Worry Where the Next Pandemic Will Come From—and If We'll Be Ready."

[9] Oak Ridge Institute for Science and Education, *Workshop Proceeding*.

[10] White House, *American Pandemic Preparedness*, p. 6.

[11] "Microbiology by Numbers," p. 628.

can lead to disease. Through reproduction or replication, pathogens often experience genomic shift and drift, resulting in new species or strains.[12] Viruses are particularly susceptible to this because they replicate very rapidly and often make errors in translation and transcription (i.e., reading and transcribing their deoxyribonucleic acid [DNA] or ribonucleic acid [RNA] into proteins) and adapt through evolutionary biology. An example would be the mutations to the spike proteins of SARS-CoV-2, which altered the rates of infection and other mutations that resulted in changes in virulence in some COVID-19 variants.

Respiratory viruses represent the likeliest pathogens for naturally occurring or synthetic pandemics (as compared with bacteria, fungi, rickettsias, and other virus classes); today, they make up almost 44 percent of all emerging infectious diseases (EIDs).[13] RNA viruses are likelier than DNA viruses to infect new host species because of their shorter generation times and faster evolutionary rates, allowing them to survive and adapt to wider environmental and host-related conditions.[14] Furthermore, single-stranded RNA (ssRNA) respiratory viruses are the most transmissible and therefore likeliest to result in a pandemic.

In terms of overall outcomes, the consequences vary greatly depending on the severity and persistence of the pandemic. However, the primary risk of pandemic comes from mortality and morbidity, with secondary risks resulting from associated societal disruptions that come as a result. As an example, the plague of Justinian from 541 CE to 767 CE resulted in global mortality estimated to be between 33 and 40 percent.[15] The decline in population in infected areas between 541 and 544 CE—in the early years of the pandemic alone—reduced the population in these affected areas by 20 to 25 percent and by 50 to 60 percent from 541 to 700 CE.[16] These percentages are much higher than those of the 1918 influenza, which killed between 50 million and 100 million globally between 1918 and 1919.[17]

In assessing the effects of pandemics, it is important to account not only for the deaths caused by the pandemic but also for the societal disruptions that the Biden administration's *National Biodefense Strategy and Implementation Plan* characterizes as "death, hospitalizations, disabilities, psychological trauma, and economic and social disruption on a massive scale."[18] The population loss during such pandemics could also result from these broader disruptions—for example, economic decline that results in mass starvation.

The pandemic risk is also affected by preparedness and response (P&R) and mitigation measures that were not available during these earlier historical examples. If applied across the global population, these measures can reduce the human suffering, mortality and morbidity rates, and the impact of the societal disruptions.

Our conclusion is that the risks from a pandemic, regardless of the cause, are continuing to increase, largely because of human behaviors. We also assessed that P&R can affect the potential for a pandemic—in some cases, P&R can lessen the likelihood that a pandemic would occur, while, in other cases, appropriate P&R measures can mitigate the effects of a pandemic that does occur.

12 Centers for Disease Control and Prevention, "How Flu Viruses Can Change."

13 Chakrabartty et al., "Comparative Overview of Emerging RNA Viruses."

14 Carrasco-Hernandez et al., "Are RNA Viruses Candidate Agents for the Next Global Pandemic?"

15 Statista, "Pre-2019 Estimates of the Plague of Justinian's Death Toll on Infected Populations from 541CE to 767CE."

16 Statista, "Pre-2019 Estimates of the Plague of Justinian's Death Toll on Infected Populations from 541CE to 767CE."

17 Wade, "From Black Death to Fatal Flu, Past Pandemics Show Why People on the Margins Suffer Most."

18 White House, *National Biodefense Strategy and Implementation Plan*, p. 2.

What Is Known About the Causes of Risk from Pandemics?

The Three Causes of Risk

The history of pandemics as a risk to human existence, the relatively small sample of the pathogens humans have encountered to date, and the growing potential to modify pathogens suggest that pandemics—whether naturally occurring or accidentally or deliberately created—represent clear catastrophic biological threats. Modern experts have uniformly assessed that the threat has increased largely because of human activity. Three reasons for this increasing threat are summarized as follows:

- New infectious diseases have been emerging at a quickening pace due to increased zoonotic transmission from animals, driven by population growth, climate change, habitat loss, and human behavior, and these diseases are spreading faster with increased global travel.
- The number of laboratories around the world handling dangerous pathogens is growing in part as a response to increasing pandemic risk, boosting the likelihood that a contagious pathogen could be released accidentally.[19]
- As the technologies of modern biology become more powerful, affordable, and accessible, there is also the disturbing possibility that a malign actor could develop and use a biological weapon, including one that is highly contagious, in violation of the Biological Weapons Convention and UN Security Council Resolution 1540.[20]

Delving more deeply into these three areas permits better understanding of these increasing risks. Natural pandemic threats are increased by "[u]rbanization, climate change, habitat encroachment, economic interdependence, and increased travel, coupled with weak health systems . . . ."[21] As species continue to come into increasingly more-frequent and closer contact, the chances of a spillover event increase accordingly. Domestication of animals, wet markets, humans encroaching into remote ecosystems, and even seeking to identify and understand new pathogens expose humans to a wider array of dangers. Human-induced climate change, urbanization, and deforestation also cause endemic species to migrate in search of new habitats. Some diseases, such as those caused by the Zika and chikungunya viruses, have become endemic across the Caribbean and into the southern states of the United States as the warming climate provides new hospitable locations for the host species and vectors that carry the diseases. These represent just a few examples of the risky behaviors that place humans at increasing danger from pandemics.[22]

In discussing the risk from EID from spillover events, Toph Allen and his colleagues concluded that "zoonotic EID risk is elevated in forested tropical regions experiencing land-use changes and where wildlife biodiversity (mammal species richness) is high."[23] They further concluded, "The majority of EIDs (and almost all recent pandemics) originate in animals, mostly wildlife, and their emergence often involves dynamic

[19] "The 1977 H1N1 influenza pandemic killed ~700,000 people. Genomic evidence suggests it may have been caused by either a laboratory accident or botched vaccine trial ([Rozo and Gronvall, "The Reemergent 1977 H1N1 Strain and the Gain-of-Function Debate"])" (this footnote appears in the original).

[20] White House, *American Pandemic Preparedness*, p. 7. *Biological Weapons Convention* (BWC) is a short reference to the Convention on the Prohibition of the Development, Production and Stockpiling of Bacteriological (Biological) and Toxin Weapons and on Their Destruction.

[21] White House, *National Biodefense Strategy and Implementation Plan*, p. 6.

[22] Senthilingam, "Seven Reasons We're at More Risk Than Ever of a Global Pandemic."

[23] Allen et al., "Global Hotspots and Correlates of Emerging Zoonotic Diseases," p. 1.

interactions among populations of wildlife, livestock, and people within rapidly changing environments."[24] The frequency of EID events more than quadrupled from 1940 to 2004.[25]

The potential for accidental biological risks continues to increase. Biological laboratories that have the capability to work with select agents, those that "pose a severe threat to both human and animal health, to plant health, or to animal and plant products," have proliferated.[26] Much of this proliferation of biological laboratories—both high-containment laboratories and biological laboratories without the necessary precautions to work with the select agents—began in the late 1990s and increased following the Amerithrax attacks that began soon after September 11, 2001.[27] This proliferation raises concerns about the potential for accidents and laboratory-acquired infections, some with pandemic potential.

A 2019 analysis of laboratory-caused pathogen exposures from 1975 to 2016 provides a "dataset of 71 incidents involving either accidental or purposeful exposure to, or infection by, a highly infectious pathogenic agent."[28] The accidents resulted from one of three causes:

- biological weapon (BW) research
- scientific research (both accidental exposure and where the "exact method of transmission is less clear")
- "incorrect labelling or distribution of a pathogen."[29]

More recently, accidental release of a pathogen has been considered as a possible start of the COVID-19 pandemic. The Office of the Director of National Intelligence conducted a 2021 assessment on the COVID-19 origins and was "divided on the most likely origin of COVID-19," and "all agencies [assessed] that two hypotheses are plausible: natural exposure to an infected animal and a laboratory-associated incident."[30] A more recent assessment by the intelligence community "rejected some points raised by those who argue COVID-19 leaked from a Chinese lab, instead reiterating that American spy agencies remain divided over how the pandemic began."[31] Although no definitive assessment has been made, the case for COVID-19 resulting from human activity is clear: The pandemic was caused by a natural spillover, escape from a laboratory like the intelligence community considered, or perhaps an alternative scenario, such as laboratory workers from the Wuhan Institute of Virology looking for samples in nature being inadvertently exposed or "exposed through improper or lax biosafety and biosecurity procedures in the laboratory."[32] Regardless of the cause of COVID-19, the debate on origins of the virus continues and points to the possibility of such laboratory-related, human activity–induced events occurring more frequently in the future.

Additionally, the democratization and deskilling of biotechnology have resulted in more people having access to the technology and less skill being required to use it, a potentially dangerous brew that could lead to more laboratory accidents and infections or the potential for dangerous experiments with little or no oversight in the case with do-it-yourself biology. Laboratory accidents and infections could also result from

[24] Allen et al., "Global Hotspots and Correlates of Emerging Zoonotic Diseases," p. 2.

[25] Jones et al., "Global Trends in Emerging Infectious Diseases."

[26] Federal Select Agent Program, "Select Agents and Toxins List."

[27] Federal Bureau of Investigation, "Amerithrax or Anthrax Investigation."

[28] Manheim and Lewis, "High-Risk Human-Caused Pathogen Exposure Events from 1975–2016."

[29] Manheim and Lewis, "High-Risk Human-Caused Pathogen Exposure Events from 1975–2016," p. 11 of 20.

[30] National Intelligence Council, *Updated Assessment on COVID-19 Origins*, p. 1.

[31] Merchant, "US Intelligence Report on COVID-19 Origins Rejects Some Points Raised by Lab Leak Theory Proponents."

[32] Gerstein, "Origin Story."

researchers not conducting experiments in proper containment, thus increasing the chances of accidents and infections.

In assessing the overall risk from laboratory accidents, one should consider the opposing risks associated with conducting or not conducting research. The historical record contains a variety of incidents that demonstrate that laboratory accidents have occurred, resulting in mortality, morbidity, and even societal consequences (such as the economic loss of livestock from having to cull herds following an inadvertent release of foot-and-mouth disease from a United Kingdom government laboratory).[33] Yet risks would also result from not doing important research, including gain-of-function and, more recently, messenger RNA vaccine research, which have resulted in better understanding of the mechanisms of action for influenza and rapid development of COVID-19 vaccines, respectively.

Deliberate biological risks have also increased, given advances in biotechnology. Since the beginning of the genomic age, people have been on a sprint to learn more about the genetic code that defines humans. Through a variety of avenues, the ability to read, write, and understand the genome (most importantly, the genotype–phenotype relationships, the relationships between gene sequences and observed characteristics) is becoming a reality. The Human Genome Project is one such avenue; continuous advances in biotechnology, such as desktop synthesizers and clustered regularly interspaced palindromic repeats (CRISPR)–associated protein 9 (Cas9), are another. Coupled with new technologies, such as AI, nanotechnology, cyber, and the Internet of Things, increasingly powerful tools will enable altering genomes and even programming life. Biotechnology will continue to become more readily available, more capable, easier to use, and less expensive.

Still, developing a BW requires mastery of five steps, each of which must be accomplished to create a viable weapon:

1. Acquire the pathogen.
2. Process the pathogen.
3. Weaponize the pathogen.
4. Develop scenarios.
5. Deploy the weapon.[34]

Failure in any one of the steps would likely prevent an actor from creating an effective BW. Certainly, some of these steps have become less challenging through the democratization and deskilling of biotech, but some degree of tacit knowledge would likely be required to create a BW. Testing would be required to ensure that the BW's desired functionality is achieved, including competent replication, that would result in a pandemic-capable pathogen. It would not be sufficient, for example, to create a pathogen in the virtual world but not test it through in vitro and in animal models prior to deploying it. Furthermore, understanding other requirements, such as self-protection during the development of a BW and the need to test the BW, would also be necessary.

Engineering a synthetic pathogen with pandemic potential becomes more feasible with the proliferation of capabilities and knowledge. Many key technologies necessary for engineering a pathogen have smaller physical footprints. In addition, more of the steps required for a successful BW attack—including a deliberate pandemic—will begin to be combined, which could facilitate both legitimate purposes (e.g., rapid development of messenger RNA vaccines) and illegitimate uses (e.g., the weaponization step's drying, formulating, and milling will likely be available in a single platform) of the biotechnology.

[33] McKie, "Foot and Mouth 20 Years On: What an Animal Virus Epidemic Taught UK Science."

[34] Gerstein, *Bioterror in the 21st Century.*

Several caveats are necessary. Predicting the likelihood that a pathogen will cause a pandemic remains challenging. Even within a single viral family, vast differences in transmissibility and virulence result in significantly different outcomes. Consider this influenza example. The 2009 swine flu pandemic, during which the death rate was "0.2–0.8 deaths per 10,000 persons," has a 3-percent probability of occurring; "an influenza pandemic causing nearly 6 million pneumonia and influenza deaths (8 deaths per 10,000 persons) or more globally is 1 percent"; and the probability of "an influenza pandemic's meeting or exceeding the global mortality rate of the 1918 Spanish flu pandemic (111–555 deaths per 10,000 persons) is less than 0.02 percent" in any given year.[35]

Second, converging technologies, such as AI, can assist in the development of a synthetic pathogen and the potential for conducting a biological weapon attack, but going from the cyber or digital world to development of an actual weapon in the physical world requires different skills and understanding. A 2023 RAND study examined how AI could be used in planning and executing such an attack.[36] The study provided information on developing a BW and even recommendations for which pathogens to use; however, it also demonstrated the limitations of using AI and large language models (LLMs) for this purpose. The output from one LLM reflected its incomplete understanding of the biology and history of biological warfare. Specifically, the AI-generated information reflected misunderstanding about which pathogen to select for a BW, where to obtain the material, and how to actually develop a BW.

Finally, because of the host–pathogen interaction, two factors make assessing the risk of a pandemic challenging. First, evolutionary biology can alter the pathogen's transmissibility and virulence. Second, errors in translation and transcription during DNA or RNA replication can create errors in the genetic sequences. Either factor can also affect a pathogen's potential to cause a pandemic.

Understanding the Risk (and Complexity) of a Synthetic Pandemic

Given that executing a successful deliberate BW attack (or creating a pandemic) directly relates to the capabilities, knowledge, and intent of a nefarious actor (whether a state or nonstate actor), both the capabilities and the knowledge have become much more widely available.[37] For a state actor and even some skilled individuals, in fact, these attributes trend toward no barriers that might inhibit the development of a BW capability. As a result, intent serves as perhaps the most important limitation for a growing population that has acquired the capabilities and knowledge to develop a BW.

For bioengineering a pandemic pathogen, any of three approaches could be employed:

- modifying an existing ssRNA virus
- performing de novo synthesis of a pathogen
- developing a chimera virus.[38]

We assessed that the first approach would require less technical skill than the other two options. De novo synthesis of a pathogen would require having an appropriate sequence and assembling the virus, which could present challenges for a bioterrorist, at least in the next decade or more. A chimera virus would entail developing a completely new species, such as a vaccinia–Venezuelan equine encephalitis chimera or a smallpox–

35 Madhav et al., "Pandemics."

36 Mouton, Lucas, and Guest, *The Operational Risks of AI in Large-Scale Biological Attacks*.

37 Gerstein, *Bioterror in the 21st Century*.

38 Gerstein, Espinosa, and Leidy, *Emerging Technology and Risk Analysis*.

Ebola virus chimera.[39] Such manipulations could be challenging to engineer, and they would not necessarily ensure that the chimera virus would have the intended functionality or capability to become a pandemic.

The variance in outcomes relates to the scope of the viral engineering and synthesis. A bioterrorist with modest skills should be able to develop a pathogen that could be deployed in a BW attack that results in mortality and morbidity; however, engineering a virus capable of replication to cause a global pandemic would not be certain. The earlier discussion of the use of AI and LLMs remains important here, and the point bears repeating: Going from the cyber or digital world to development of an actual weapon in the physical world requires different skills and understanding. Engineering a synthetic pathogen for an initial biological attack would likely be successful in causing disease. However, once a pathogen interacts with human hosts, the interactions with the host's immune system could result in changes to the viral genome and therefore the functionality of the virus. Some of these changes would result from evolutionary biology or finding mechanisms to proffer preferential characteristics (such as an increase in the transmissibility of the virus), while others might be due to translation and transcription errors during replication. As a result, the virus could become more or less transmissible, as well as more or less virulent. However, mechanisms do not currently exist to fully understand how these changes would be likely to affect a pathogen and thus the characteristics of the pandemic it would cause. The challenges in understanding the genotype–phenotype relationship can be seen in comparing three recent coronavirus outbreaks: SARS, Middle East respiratory syndrome (MERS), and COVID-19. The viruses were very similar in their genomes but quite dissimilar in the scope, scale, and severity of the diseases they caused.[40]

Despite these new technologies, challenges would remain. Today, researchers have an incomplete understanding of the genotype–phenotype relationships, which creates uncertainties for engineering genome sequence modifications that result in the desired pathogen characteristics (i.e., transmissibility and virulence) while remaining replication competent. More on the implications of this limitation is discussed in the next section.

In summary, in terms of the risk of a deliberate BW attack, synthesizing and deploying a pathogen would likely be successful for either a noncontagious or contagious pathogen. People in the primary aerosol-release area would receive overwhelming doses and would experience incubation times, severity of the illness and outcomes far direr than the natural forms of the disease. In attempting to provoke a pandemic, the challenge would be to synthetically engineer a replication-competent, contagious pathogen (i.e., a replication rate [R0] of greater than 1 that would efficiently support secondary infections through human-to-human transmission). As a result, predicting an outcome with great certainty continues to be challenging.

Uncertainty of Risk from Pandemics

An interesting point of departure for understanding the uncertainty about risk of pandemics pertains to the global mortality associated with the plague of Justinian from 541 CE to 767 CE, which ranged from 33 to 40 percent.[41] The population in infected areas between 541 to 544 CE—in the early years of the pandemic—dropped by 20 to 25 percent and, between 541 and 700 CE, by 50 to 60 percent.[42] These percentages are much greater than those of the 1918 influenza, which killed between 50 million and 100 million globally in 1918 and 1919.[43]

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39 Alibek, *Biohazard*.

40 Hewings-Martin, "How Do SARS and MERS Compare with COVID-19?"

41 Statista, "Pre-2019 Estimates of the Plague of Justinian's Death Toll on Infected Populations from 541CE to 767CE."

42 Statista, "Pre-2019 Estimates of the Plague of Justinian's Death Toll on Infected Populations from 541CE to 767CE."

43 Wade, "From Black Death to Fatal Flu, Past Pandemics Show Why People on the Margins Suffer Most."

In assessing the effects of pandemics, it is important to account not only for the deaths caused by the pandemic but also for the societal disruptions caused by "death, hospitalizations, disabilities, psychological trauma, and economic and social disruption on a massive scale."[44] The population loss during such pandemics could also result from these broader disruptions.

For example, the total number of global COVID-19 cases and deaths were 770,778,396 and 6,958,499, respectively, as of September 21, 2023; the U.S. total cases and deaths were 103,436,829 and 1,127,152, respectively. This makes COVID-19 the fifth-largest recorded pandemic.[45] However, despite these death tolls, even seasonal influenza epidemics routinely cause widespread mortality and morbidity. According to John Paget and his colleagues, the global mortality estimates for 2017 were "290 000 to 650 000 influenza-associated respiratory deaths annually."[46] However, the disruptions caused by pandemic-related nonpharmaceutical interventions, such as social distancing, masking, isolation, and quarantines, also affect societies. During the height of the COVID-19 pandemic, entire industries and supply chains experienced severe disruptions.[47] Despite the high figures for mortality and morbidity in the historical examples above, humans have demonstrated remarkable resilience in the pandemics throughout recorded history.

In thinking about how large a pandemic could be, an excursion for argument's sake could use the 20- to 25-percent drop in population in the early years of the Justinian plague pandemic from 541 to 544 CE and do a linear projection for a global population of 10 billion people in 2050.[48] This would equal 2 billion to 2.5 billion people dying as a result of a pandemic. However, a note of caution and dose of realism are required in considering such an estimate. Global public health is far better than it was 1,600 years ago, and pharmaceutical interventions and nonpharmaceutical interventions have improved significantly during that time frame.

This last point about pharmaceutical and nonpharmaceutical interventions is profound because it implies that the risks from certain pathogens have changed dramatically. For example, the risks from pandemics caused by bacterial agents, such as *Yersinia pestis*, the causative agent of the bubonic plague (the culprit in the Justinian plague and the Black Death), are not likely to be as high now because humans have developed methods for vector control that are now readily available. Likewise, the smallpox virus is unlikely to present the same threat as it has historically because vaccines and medical interventions, such as antivirals, are now available, and the disease has been eradicated in the wild once using ring vaccination.

On the challenges of predicting the risk of a pandemic, one source states,

> No single disease currently exists that combines the worst-case levels of transmissibility, lethality, resistance to therapies, and global reach. But we know that the worst-case attributes can be realized independently. For example, some diseases exhibit nearly a 100% case fatality ratio in the absence of treatment, such as rabies or septicemic plague. The 1918 flu has a track record of spreading to virtually every human community worldwide. Chickenpox and HSV-1 [herpes simplex virus 1], can reportedly reach over 95% of a given population.[49]

This is a useful way to think about the relationship between the different pathogen characteristics and their effect in causing a pandemic (resulting from achieving an R0 of greater than 1). If a virus is particularly

[44] White House, *National Biodefense Strategy and Implementation Plan*, p. 2.

[45] White House, *National Biodefense Strategy and Implementation Plan*.

[46] Paget et al., "Global Mortality Associated with Seasonal Influenza Epidemics," p. 2; WHO, "Influenza."

[47] Gerstein, *The Federal Research Enterprise and COVID-19*.

[48] Department of Economic and Social Affairs, "World Population Projected to Reach 9.8 Billion in 2050, and 11.2 Billion in 2100."

[49] Besiroglu, "Ragnarök Question Series."

deadly and symptoms come very quickly after initial infection, the host will likely be too sick to go about their daily business and therefore not able to transmit the virus to others. In such a case, the host would likely succumb to the disease before widespread transmission could occur.

In seeking to understand the possibility of future pandemics occurring, experts have considered numerous scenarios. Piers Millett and Andrew Snyder-Beattie reported an "annual probability of a global pandemic resulting from an accident with this type of research in the United States is 0.002% to 0.1%," which, when evaluated globally, translated to a "0.016% to 0.8% chance of a pandemic in the future each year . . . ."[50]

Piers Millett and Andrew Snyder-Beattie arrived at definitions for pandemics based on mortality: crisis (100,000 or more deaths), global catastrophic risk (100 million or more) and existential risk (7 billion or more, including future generations).[51] The authors highlighted the limited information on biological warfare, calling actual state use of BWs "less common."[52] Through extrapolation, the study team also concluded that the annual chance per year of biowarfare was 20 percent. They also referenced a 2008 informal survey at the Oxford Global Catastrophic Risk Conference, in which respondents indicated "a median risk estimate of 0.05% that a natural pandemic would lead to human extinction by 2100, and a median risk estimate of 2% that an 'engineered' pandemic would lead to extinction by 2100."[53]

In evaluating the data, Millett and Snyder-Beattie indicated that such low probabilities should not be comforting, given that their "models are based on historical data, [so] they fail to account for the primary source of future risk: technological development that could radically democratize the ability to build advanced bioweapons."[54] Finally, in considering extrapolations of historical data, the authors concluded, "Assuming that 10% of biowarfare escalations resulting in more than 5 billion deaths eventually lead to extinction, we get an annual existential risk from biowarfare of 0.0000005 (or 5×10^{-7})."[55] The article continues, "[I]f we were to assume that humanity would otherwise maintain a global population of 10 billion for the next 1.6 million years, human extinction would jeopardize on the order of 1.6×10^{16} life years."[56]

Toby Ord arrived at values for "existential catastrophe" in the next 100 years via "naturally arising pandemics" and "engineered pandemics" as 1 in 10,000 and 1 in 30, respectively.[57] In justifying these figures, Ord offered that, in making these risk assessments, "We may have too little data" and highlighted the likely effects of trends in biotechnology and its increasing democratization in the next century.[58] Taken together, he asserted, these observations prevent one from relying on normal distributions in making assessments about

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50 Millett and Snyder-Beattie, "Existential Risk and Cost-Effective Biosecurity," p. 377.

51 Millett and Snyder-Beattie, "Existential Risk and Cost-Effective Biosecurity."

52 Millett and Snyder-Beattie, "Existential Risk and Cost-Effective Biosecurity," p. 375.

53 Millett and Snyder-Beattie, "Existential Risk and Cost-Effective Biosecurity," p. 376.

54 Millett and Snyder-Beattie, "Existential Risk and Cost-Effective Biosecurity," p. 378.

55 Millett and Snyder-Beattie, "Existential Risk and Cost-Effective Biosecurity," p. 377.

56 Millett and Snyder-Beattie, "Existential Risk and Cost-Effective Biosecurity," p. 378, citing calculations in Matheny, "Reducing the Risk of Human Extinction."

57 Ord, *The Precipice*, p. 167.

58 Ord, *The Precipice*, p. 167.

future risk. Instead, Ord wrote, "patterns of disease appear to follow power law distributions," similar to the approach followed by Millett and Snyder-Beattie.[59] He added,

> Unlike the familiar "normal" distribution where sizes are clustered around a central value, power law distributions have a "heavy tail" of increasingly large events, where there can often be events at entirely different scales with some being thousands, or millions, of times bigger than others.[60]

Despite the relatively sparse number of incidents from which to draw trends and conclusions, some necessary, and often complex, steps must be undertaken to conduct a biological warfare attack, including developing and deploying a synthetic pathogen to create a pandemic. Each of these steps requires a degree of capability, knowledge, and intent to be able to develop a viable BW. In "Bioterror in the Age of Biotechnology," Daniel Gerstein asserted, "several factors contribute directly to the ability to develop and employ an effective biological weapon, including the agent or pathogen, deployment method, formulation, manufacturing process, and meteorological and terrain conditions."[61] The perpetrator must also be able to manage (and, in some cases, control) technical aspects of an attack, including the concentration of the pathogen, the dose received by the host, the stability of the pathogen in the air, and the target's susceptibility. Failure to successfully accomplish any one of the steps or control for any of the pathogen's key attributes during the attack could prevent a bioterrorist from successfully executing an attack. Uncertainty also exists based on prevention, mitigation, and response capabilities that can serve to reduce the probability or effectiveness of a successful attack.[62]

Despite advances in capabilities and knowledge, assessing the likelihood of a successful attack (or deliberate pandemic) remains problematic because intent—which guides how the capabilities and knowledge will be used—remains a challenge. Strong international norms against the use of BWs exist, including the Biological Weapons Convention, which appears to have moderated behaviors. The BWC also requires that signatory countries establish national laws that prohibit "the development, production, acquisition, transfer, stockpiling and use of biological and toxin [sic] weapons."[63] Some experts have also concluded that limits emanate from what terrorism scholar Jessica Stern identified in her assessment:

> Biological agents are mysterious, unfamiliar, indiscriminate, [uncontrollable], inequitable, and invisible, all of which are characteristics of dreaded risks. The effects of these weapons are also difficult to predict and poorly understood by science. They are physically disgusting, a factor associated with moral aversion.[64]

In another assessment, Gerstein developed a game-theory approach to assess the question of whether some self-imposed limitations have been deterring nefarious actors from employing BW.[65] He concluded that actors likely perceive a point at which it is in their interest to discuss the use of BW but that an attack would likely become an existential threat to the terrorist and their cause.

Although engineering a synthetic pathogen with pandemic potential becomes more feasible with the proliferation of capabilities and knowledge, challenges would remain. Today, the incomplete understanding of

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[59] Millett and Snyder-Beattie, "Existential Risk and Cost-Effective Biosecurity"; Ord, *The Precipice*, p. 167.

[60] Ord, *The Precipice*, p. 167.

[61] Gerstein, "Bioterror in the Age of Biotechnology," p. 81.

[62] Gerstein, "Glaring Gaps."

[63] Office for Disarmament Affairs, "Biological Weapons Convention."

[64] Stern, "Dreaded Risks and the Control of Biological Weapons," p. 121.

[65] Gerstein, "Bioterror in the Age of Biotechnology."

the genotype–phenotype relationships creates challenges for engineering genome modifications that result in the desired pathogen characteristics (i.e., transmissibility and virulence) while remaining replication competent and capable of human-to-human transmission. We anticipate that, in the next 30 years or so and certainly by 2100, many, if not most, of these challenges are likely to be overcome.

Additionally, significant uncertainty exists about whether a sustained synthetic pandemic can be created based on such factors as evolutionary biology, the pathogen–host interaction, and the pathogen's stability to remain capable of human-to-human transmission. If the R0 cannot be sustained above 1, the pandemic will end.

In terms of the uncertainty and timing of risks, biological warfare has relatively few historical precedents from which one can confidently assess the risks of a future BW attack—specifically, a synthetic pandemic. However, we can conclude that biotechnology capabilities and knowledge will continue to proliferate and become more readily available to a wider variety of actors. These increases will contribute to an increased risk of a synthetic pandemic. Still, actors considering use of biological pathogens as weapons appear to be deterred in some way. Obviously, this could change, especially as the capabilities and knowledge allow smaller groups or even lone actors to access or develop pandemic potential pathogens and the means to prepare them to use as weapons.

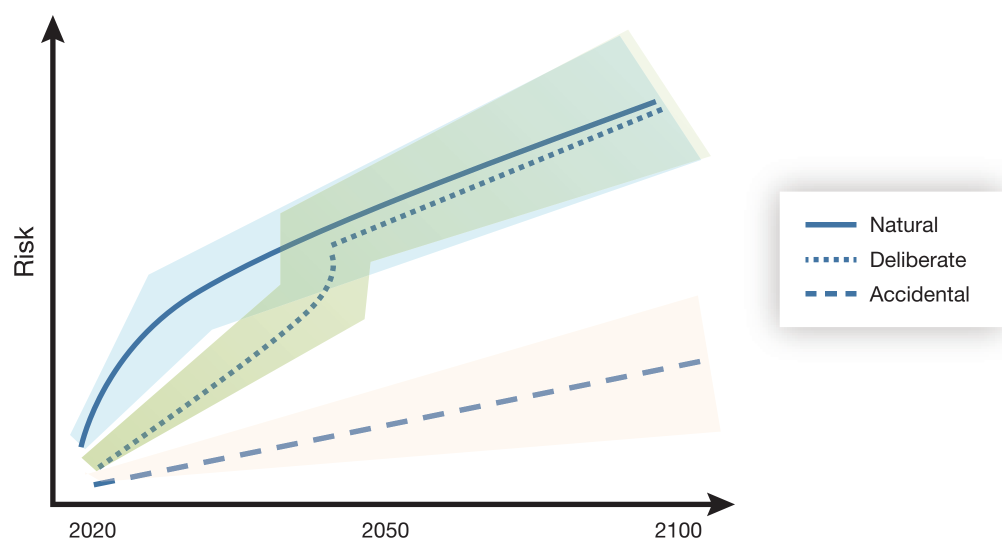
How the Risk from Pandemics Will Evolve

The risk of pandemics will continue to evolve based on human behaviors. This will occur for each pandemic type: natural, accidental, or deliberate. Figure 6.1 depicts a relative comparison between the three types of potential causes of pandemics. These assessments are not intended to be predictions but rather to compare the perceived risk out to 2100.

For natural pandemics, human encroachment into natural habitats and ecosystems, coupled with increasing interactions with humans, will increase the chances of a spillover event. Based on the increased frequency observed in the past 100 years, a doubling or even quadrupling of the frequency is possible. This frequency could result in a COVID-19–like pandemic occurring every 25 to 50 years rather than the 100 years between the 1918 influenza pandemic and the COVID-19 pandemic. However, it is worth restating that a natural pan-

FIGURE 6.1

How the Risks of Three Types of Pandemic Could Evolve over Time



demic would occur and be sustained based on evolutionary biology, the pathogen–host interaction, and the pathogen's stability to remain capable of human-to-human transmission.

For a deliberate pandemic, the most effective way to deliver a pandemic pathogen is through the aerosol route. An actor would need to go through each of the five steps required for a BW attack, including conducting an initial attack. The availability of capabilities and knowledge to develop a BW (whether with a noncontagious or a contagious pathogen) means that the likelihood of conducting a successful attack (i.e., one with high mortality and morbidity) is becoming likelier with advances in biotechnology. As a result, those in the aerosol-release plume receiving an overwhelming dose would likely experience severe symptoms resulting in dire outcomes. However, once the pathogen begins to interact with a human host, through evolutionary biology to gain preferential characteristics and translation and transcription errors during replication, the pathogen would be altered. Whether the pathogen would retain the transmissibility to result in a pandemic (i.e., an R0 greater than 1) is not possible to predict (at least not with the current understanding of genotype–phenotype relationships).

Several experiences demonstrate how attempting to engineer pathogens and even minor differences in genomic sequences can have important effects. In the highly pathogenic avian H5N1 influenza A experiments that resulted in the development of the policy on dual-use research of concern, which limited government-sponsored work on gain-of-function experiments, the findings demonstrated the challenges with trying to engineer a pathogen. The goal of the studies was to determine in a ferret model whether the transmissibility of the virus could be enhanced while retaining the extremely high virulence (i.e., about 60 percent) of the virus.[66] In summarizing the result, one account stated,

> We identified a reassortant H5 HA/H1N1 virus—comprising H5 HA (from an H5N1 virus) with four mutations and the remaining seven gene segments from a 2009 pandemic H1N1 virus—that was capable of droplet transmission in a ferret model. The transmissible H5 reassortant virus preferentially recognized human-type receptors, replicated efficiently in ferrets, [and] caused lung lesions and weight loss, but was not highly pathogenic and did not cause mortality.[67]

In other words, when the transmissibility was increased, the pathogen's virulence decreased.

Understanding the genotype–phenotype relationship will continue to be complex and subject to significant uncertainties. For example, SARS, MERS, and COVID-19 are diseases caused by coronaviruses and have approximately 96-percent similarity in their genomes yet have very different etiologies. SARS is transmissible between humans but is not nearly as infectious as COVID-19. SARS has a higher rate of case fatality, but it does not transmit asymptomatically the way COVID-19 does. MERS has not been shown to be human-to-human transmissible and has a much higher mortality rate than either SARS or COVID-19.

Thanks to AI and experimentation, the genotype–phenotype relationships will likely become better understood. However, only through testing in vitro and in vivo can a virus's etiology be fully understood. This is made more challenging by the fact that in vivo testing involves animal models, which serve only as surrogates for human testing (which would be barred by rules on research ethics). Regardless of the amount of testing, predicting outcomes is fraught with uncertainties.

A factor that reduces the likelihood and, therefore, the risk of a deliberate pandemic is the norms against the use of BWs. Quantifying the effect of these norms remains challenging, but they cannot be discounted. Although some have suggested that a lone actor could create a synthetic pandemic, this would likely remain

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[66] Schmidt, "Gain-of-Function Research."

[67] Imai et al., "Experimental Adaptation of an Influenza H5 HA Confers Respiratory Droplet Transmission to a Reassortant H5 HA/H1N1 Virus in Ferrets," p. 420.

challenging in the near term, given the complexities associated with developing the capabilities, knowledge, and intent that would need to be mastered for an initial successful attack and follow-on pandemic.

As a result, it seems unlikely that a deliberate pandemic (even employing synthetic engineering) would exceed the risk of a natural pandemic in the next decade. Perhaps over a 30-year horizon or by 2100, this assessment could change. However, through evolutionary biology, pathogens have adapted over billions of years. For an actor engineering a pathogen, the desired characteristics, such as virulence, transmissibility, and disease mechanism of action (i.e., how the disease affects the host), would need to be understood and engineered into the synthetic pathogen. This is a nontrivial issue at the time of this writing, especially given incomplete understanding of the human genome and the genome of the pathogen to be engineered.

As a result, in Figure 6.1, we depict the natural pandemic as the greater initial risk than deliberate pandemic. Assuming that the genotype–phenotype relationships become clearer, the risk of the natural spillover and a deliberate pandemic would trend toward being roughly equivalent. Still, little precedent exists to support an existential risk of either a natural spillover or a deliberate pandemic.

For a catastrophic risk of either a natural spillover or a deliberate pandemic, there is little precedent on which to base this assessment. In making these judgments, we in no way intend to minimize the suffering or societal disruptions that have occurred during past pandemics. However, we seek to characterize a large-scale pandemic on the order of magnitude of either COVID-19 (roughly 7 million deaths) or the 1918 influenza (50 million to 100 million deaths), which was one to two orders of magnitude greater than COVID-19, as becoming increasingly likely, given human activities.[68]

For accidental pandemics, the primary source considered was laboratory leaks—this is in keeping with the Biden administration's 2022 *National Biodefense Strategy and Implementation Plan*'s portrayal of the accidental risk.[69] In general, laboratory leaks of pandemic-capable pathogens would be less likely given the discrete locations where experiments with dangerous pathogens are likely to be conducted and measures taken to safeguard these facilities and the work done within them. In making this assessment, we assumed that biosafety and biosecurity measures would be undertaken that would reduce the overall risks associated with such leaks during the time frame considered. For example, laws, policies, and regulations; standards and norms of behavior; codes of ethics; personnel reliability programs; physical protection of laboratory facilities; emergency response capabilities, and human-subject protections all serve to reduce the risks of an accidental release.

By way of an excursion based on COVID-19 data as a starting point for considering the potential magnitude of a pandemic (i.e., regardless of the source, naturally occurring, accidental, or deliberate), consider that COVID-19 has resulted in approximately 770 million cases and 7 million deaths (as of September 2023).[70] A scenario can be envisioned in which the 770 million cases—which represent approximately 10 percent of today's global population[71]—could be increased to infect a higher percentage of the global population. However, even doubling the case fatality rate to 2 percent—which would equal approximately 15 million deaths—would not represent an existential threat to humans. Even if one-quarter of the approximately 8 billion people in the world (2 billion people) were infected and the case fatality rate were 10 percent, 200 million people would die. Although this would certainly be highly consequential and cause significant societal disruption, it would likely not threaten human existence.

In ending this section, we provide some overarching conclusions on the likelihood of future pandemics.

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[68] For COVID-19 data, see Health Emergencies Programme, "WHO COVID-19 Dashboard."

[69] White House, *National Biodefense Strategy and Implementation Plan*.

[70] Health Emergencies Programme, "WHO COVID-19 Dashboard."

[71] United Nations, "Population."

Conclusions on the Risk of a Pandemic

The frequency of pandemics—regardless of whether they are naturally occurring, accidental, or deliberate—is likely to increase because of human activity.

- A high probability exists that a naturally occurring pandemic with case numbers and fatalities equal to or greater than those of the COVID-19 pandemic will occur and that the next pandemic is unlikely to be 100 years in the future (i.e., as COVID-19 was in comparison to the 1918 influenza pandemic).
- The stresses and factors brought on by more interaction between species, climate change, and globalization will provide more opportunities for spillovers; we estimate that this could increase the frequency of naturally occurring pandemics by two to four times through 2100.

Significant uncertainties exist with respect to the probability of either a deliberate or accidental pandemic.

- Little precedent exists for large-scale biological attacks, including for deliberately introducing a pandemic. Despite this uncertainty, the capabilities and knowledge to develop, modify, or obtain a highly pathogenic respiratory virus have increased. Assessing the intent of a potential bioterrorist actor is far more complex than assessing capabilities and knowledge.
- There is significant uncertainty about an accidental release from a lab that would cause a pandemic. Biosafety and biosecurity measures provide guardrails to minimize such a likelihood but are not necessarily foolproof.

There are great uncertainties in predicting whether a pandemic caused by either a natural spillover or a deliberate attack could be a catastrophic or existential risk.

- A pathogen could be engineered to be transmissible and virulent; however, there is no assurance that it would remain so over a prolonged period because evolutionary biology and translation and transcription errors during viral reproduction could alter the pathogen's invasiveness or virulence.
- Interactions with the host's immune system would result in unpredictable changes to the pathogen, which could affect transmissibility and virulence.

What Has Been and Could Be Done to Manage Risk from Pandemics?

An exhaustive discussion of risk mitigation is beyond the scope of this report. However, in a general sense, understanding the interactions of the host and the pathogen through the lens of the replication rate—or the number of people that each infected person infects—provides insights into risk management and mitigation. The higher the R0, the greater likelihood of a pandemic. Obviously, the converse is also true.

The probability of a pandemic occurring is based on human exposure to a pathogen with an R0 greater than 1, meaning that the pathogen would efficiently support secondary infections through human-to-human transmission. Factors that directly influence R0 are

- human activity, such as interactions with species, climate change, and deforestation
- pathogen characteristics, such as virulence (infectious or lethal dose) and transmissibility (method of transmission, asymptomatic transmission)
- nonpharmaceutical intervention, such as physical distancing, masking, closures, and quarantine
- pharmaceutical interventions, such as medical countermeasures (MCMs), vaccines, therapeutics, and supportive care

- susceptibility of the population, such as the pathogen–host relationship and public health
- P&R, such as exercises, stockpiling, and emergency management doctrine
- fog and friction, such as societal adherence to public health guidance and understanding of the disease etiology.

Furthermore, it remains paramount to understand that R0 is not a fixed number but rather has key dependencies related to human activity, pathogen characteristics, pharmaceutical and nonpharmaceutical interventions, susceptibility of the population, P&R capabilities, and fog and friction. Table 6.2 lists the mitigation options we have identified.

The aforementioned dependencies are not independent of one another, and the relationships between them are complex. For example, human activity and pathogen characteristics can combine to affect the chance of a pandemic. The more interaction between humans and animals (particularly, domesticated animals) increases the chances of a spillover event. For example, pigs serve as an ideal "mixing vessel" for influenza, and the 2009 influenza pandemic "contained genes from pig, bird and human influenza viruses, in a combination that had not been reported before in any part of the world."[72] Nonpharmaceutical interventions, pharmaceutical interventions, and P&R activities reduce the overall risk of a pandemic and decrease the population's susceptibility. Fog and friction have been used to highlight the uncertainties about pandemics; the phrase is meant to highlight that, in any incident response or associated plan, uncertainties occur that perhaps were not foreseen, understood, or sensed in sufficient time to react to mitigate the risk.

Summary

The risk of pandemics—either naturally occurring, resulting from an accidental laboratory release, or deliberately perpetrated—is growing largely because of human behaviors. In making this assessment, several key factors undergird the analysis. First, we were driven by the focused scope of the study topic, which was given as assessing the risk of a pandemic. Second, we used the WHO definition for *pandemic*, including the articulation of the pandemic phases. Taken together, this implies that a pandemic pathogen should have the capacity to cause human-to-human transmission and outbreaks at the community level, with the higher-

TABLE 6.2
Pandemic: Overview of Risk Mitigation Opportunities

Mitigation Dimension	Mitigation Option
Reduce the likelihood of occurrence.	Reduce human activities that contribute to naturally occurring, accidentally laboratory-induced, or deliberately caused pandemics, and reduce susceptibility through vaccination against the likeliest threats.
Disrupt the mechanisms leading to risk.	Reduce pandemic risk by addressing habitat encroachment, unsafe lab experiments, and misuse of technology.
Reduce the severity of effects.	Develop pandemic preparedness measures and increase confidence in government institutions responsible for pandemic planning and response.
Enhance response and recovery.	Shorten timelines for development of medical countermeasures. Improve strategic communications.

[72] European Centre for Disease Prevention and Control, "Factsheet on Swine Influenza in Humans and Pigs."

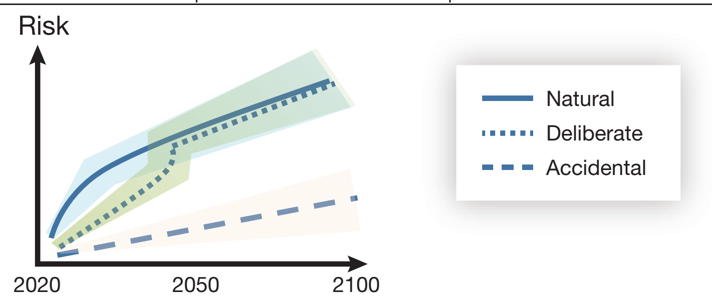
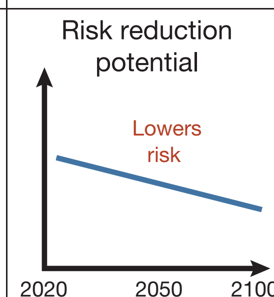
numbered phases indicating greater severity and spread of the disease.[73] These specifications lead to the conclusion that the most-dangerous pandemics would be caused by respiratory pathogens, and experts have assessed that ssRNA respiratory viruses are most transmissible and therefore likeliest to result in a pandemic.

Figure 6.2 compares the pandemic risks associated with naturally occurring, accidentally laboratory-released, and deliberate pandemics caused by an engineered pathogen. Detailed explanations of the rationale for the relative risks between the three pandemic types were provided in the "How the Risk from Pandemics Will Evolve" section of this chapter. The figure also provides insights into how P&R can affect the potential for a pandemic—in some cases, P&R can lessen the likelihood that a pandemic will occur, or appropriate P&R measures can mitigate the effects of a pandemic that does occur. Our overall conclusion is that the risks from a pandemic, regardless of the cause, are continuing to increase, largely because of human behaviors.

[73] Global Influenza Programme, *Pandemic Influenza Preparedness and Response*.

FIGURE 6.2

Pandemic Risk Assessment Considering Preparedness and Response Measures

	Natural Pandemic	Accidental Pandemic	Deliberate Pandemic	Preparedness and Response (P&R)	Pandemic Risk Assessment Comparison
Rationales for Assessment	• More people and more travel results in greater risk of a pandemic • Human infringement into natural ecosystems • Frequency of COVID-19–like pandemic likely to increase (2–4 times) • Pandemic from a naturally occurring pathogen becomes more likely because of human activity	• More labs, but safer environment for experiments • Expectations of increased biosafety and biosecurity • Laws, policies, regulations; norms and standards codes of ethics; and personnel reliability programs serve to reduce the risks of an accidental release	• Deskilling and democratization of biotech means more actors using biotech • Societal norms against the use of biological pathogens • Unpredictability of the pathogen pandemic potential means attack might not be successful • Knowledge of pathogen genomic sequences and observed characteristics in the future increases chance of successful attack	• Biotech and new approaches to MCMs • Biosurveillance and diagnostics improvements • Changing nature of disease response • Personalized medicine	• Increasing risks of occurrence for all three pandemic types • Frequency of COVID-19–like pandemic likely to increase (2–4 times) • Lower likelihood of accidental and deliberate than a naturally occurring pandemic in next decade • Greater capability for P&R means faster response and less societal disruption
Trends in Risk					

CHAPTER 7

Rapid and Severe Climate Change: Summary of Risk

Human-induced changes in the climate system, largely associated with past and future emissions of GHGs, will have significant adverse effects on the global environment and, by extension, human well-being. Climate change–related disruptions to the natural environment have implications for weather patterns, sea levels, food and water security, and infrastructure, thereby posing a risk to human health, the economy, and national security. Table 7.1 provides an overview of the risks.

Research in the past decade has revealed that many elements of the Earth system can be disrupted at relatively modest magnitudes of global warming, and there are plausible pathways by which more-severe climate

TABLE 7.1
Climate Change: Overview of Risk

Risk Dimension	Assessment for Severe Climate Change
Most-significant consequences	Primary • Death • Disruption • Degradation of ecosystem stability Secondary • Slowing of economic growth and reductions human capabilities induced by environmental, economic, and ecosystem damage
Factors that influence the magnitude of risk	• The climate system's sensitivity to GHG emissions • Future actions taken to reduce future GHG emissions • Future population and infrastructure exposure and existing vulnerability to climate hazards • Future actions to reduce exposure and enhance resilience • Extent of risk propagation across social and ecological systems
Likelihood of risk	• The probability of global warming more than 2.0°C in the 21st century is greater than 90% given current emission trajectories. Warming of this magnitude is considered catastrophic on a local to regional scale but is not projected to generate global catastrophic loss. • The probability of more-severe global warming more than 4.0°C is estimated at less than 1% for the 21st century. Warming of this magnitude increases the risk of more-widespread catastrophic outcomes.
Temporal nature of the risk and change in the next decade	• Climatic consequences of climate change will continue to escalate in future decades but will manifest in different places over different time horizons. Climatic consequences will include acute events, such as extreme weather events, and chronic events, such as sea-level rise or ecosystem degradation. • Current climate conditions and risk serve as proxies for conditions in the next decade.
Quality of the evidence supporting the assessment	• High-quality observations of atmosphere, ocean, and land surface changes • Robust projections of future changes in global average temperature change by 2050, with greater uncertainty in later decades • Significant uncertainty about changes in climate hazards (e.g., storms, wildfire, droughts), particularly at local to regional scales, as well as thresholds for tipping points in various elements of the Earth system • High uncertainty about how risk cascades across systems or how multiple, compounding events interact to affect food security, human migration, and conflict

change could arise. However, global climate risk is not the result of a single catastrophic event but rather of the cumulative effects of many adverse events that manifest over different geographic scales and time horizons. Changes in the climate have implications for weather patterns, sea levels, food and water security, and the operation of infrastructure. Although such risks are increasingly referred to as being catastrophic or existential, these concepts have been poorly defined in both the scientific and policy communities. Nevertheless, continued growth in global GHG emissions is associated with a greater risk of adverse outcomes.

What Is Known About the Causes of Risk from Rapid and Severe Climate Change?

Researchers have been warning about the potential catastrophic and even existential threats of climate change since at least 1989.[1] In just the past decade, researchers have published findings from thousands of studies warning of dire consequences associated with human-induced climate change. International scientific assessments, such as those from the Intergovernmental Panel on Climate Change (IPCC), and the U.S. National Climate Assessment have critically examined this rich body of literature and documented a broad assortment of reasons for concern about climate change. The alarms about climate change are no longer being sounded just by the scientific community. The United Nations, for example, has declared a global "climate emergency," and 194 countries and the European Union have ratified the Paris Agreement and committed to limiting global GHG emissions.[2]

Despite such warnings, catastrophic consequences of climate change do not arise from a single cause-and-effect relationship like some of the other risks documented in this report (e.g., asteroid impacts or nuclear war) do but rather through a complex sequence of interactions between human decisions and actions and the Earth system. Therefore, to understand the risk of climate change—particularly, low-probability, high-consequence events—one must understand the pathways by which climate change affects society, the critical thresholds that would trigger catastrophic outcomes, and the chain of events that would have to transpire for those outcomes to be realized.

Effect Pathways

The effects associated with climate change emerge from a multistage pathway (Figure 7.1). GHG emissions from natural processes and human activities increase concentrations of GHGs in the atmosphere. This, in turn, increases the radiative forcing of the atmosphere. When radiative forcing is positive (in directionality), the atmosphere traps more energy from the sun than what is being released into space. This contributes to a rise in global temperatures and drives downstream changes in various Earth systems that are important for regulating the planet (Figure 7.1). For example, rising atmospheric and ocean temperatures drive changes in weather and climate patterns.[3] Although natural processes have driven changes in atmospheric GHG concentrations throughout Earth's history, here we focus on human drivers of climate change because their effects have dominated natural climate drivers since the Industrial Revolution.[4]

One of the most-fundamental responses to increased radiative forcing is changes in patterns of atmospheric and ocean circulation. For example, the jet stream is a major mechanism by which heat is transferred

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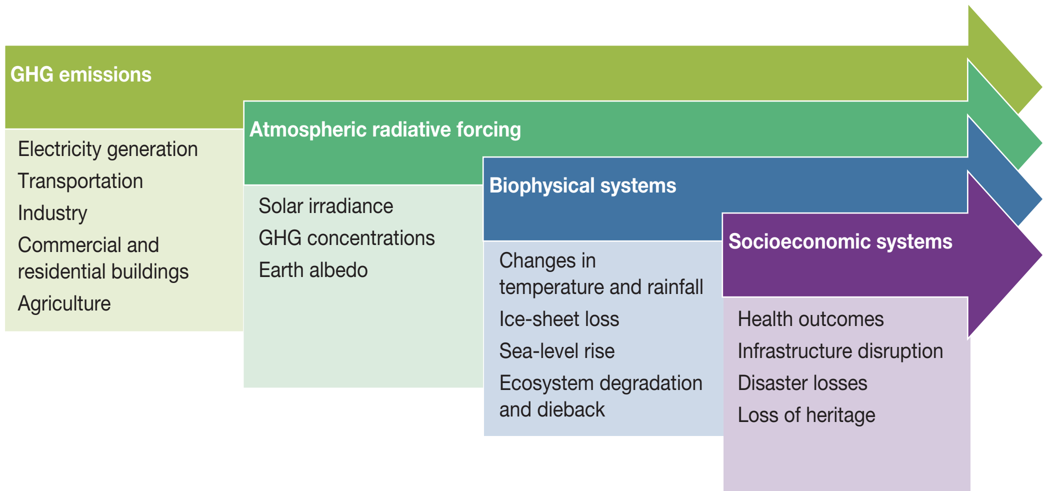
1 Butler, "Climate Change, Health and Existential Risks to Civilization."

2 United Nations, "The Paris Agreement"; United Nations Environment Programme, *The Closing Window*.

3 IPCC, "Summary for Policymakers," 2021.

4 IPCC, "Summary for Policymakers," 2021.

FIGURE 7.1
Climate Driver Effect Pathways



from one region of the world to another. It is also often associated with extreme weather events, including both extreme cold events (e.g., polar vortex events) and extreme heat events and heat waves. Recent research suggests that climate change could cause changes in the jet stream that would drive more-frequent and more-severe weather patterns.[5] Meanwhile, ocean circulation, one of the planet's greatest climate-system stabilizers, can be weakened by warming waters, reducing nutrient mixing and the distribution of heat across regions, further driving changes in weather and climate patterns, and affecting marine life.[6] Moreover, oceans are absorbing carbon dioxide (CO_2) at an unprecedented rate, changing ocean chemistry, which has implications for food security and ways of life for many cultures that heavily depend on the oceans and marine life.[7] Changes in ocean temperatures, chemistry, and currents occur over longer periods than changes in the atmosphere do, so trends can persist for decades.

The warming climate is also a driver of global and regional sea-level rise. Increases in sea levels are a result of thermal expansion of the oceans and the melting of glaciers and polar ice sheets (particularly over Greenland and Antarctica).[8] These increasing sea levels exacerbate storm surge, coastal erosion, and, ultimately, higher groundwater levels, salinization of freshwater resources, and the permanent inundation of low-lying coastal lands. Rises in ocean temperatures also contribute to the development of stronger storms in the tropics and can shift precipitation patterns,[9] increasing intense rainfall and flooding in some regions while worsening drought and wildfire risks in other.

Global concern about climate change is largely a function of the implications for the sustainability of ecosystems and their services, such as food and water, as well as direct effects on human health and safety,

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5 Moon et al., "Wavier Jet Streams Driven by Zonally Asymmetric Surface Thermal Forcing"; Woollings et al., "Trends in the Atmospheric Jet Streams Are Emerging in Observations and Could Be Linked to Tropical Warming."

6 Liu et al., "Reduced CO_2 Uptake and Growing Nutrient Sequestration from Slowing Overturning Circulation."

7 Doney et al., "The Impacts of Ocean Acidification on Marine Ecosystems and Reliant Human Communities"; Leung, Zhang, and Connell, "Is Ocean Acidification Really a Threat to Marine Calcifiers?"

8 Sweet et al., *Global and Regional Sea Level Rise Scenarios for the United States*.

9 Russell et al., "Investigating the Association Between Late Spring Gulf of Mexico Sea Surface Temperatures and U.S. Gulf Coast Precipitation Extremes with Focus on Hurricane Harvey."

infrastructure, economic activity, and national security.[10] For example, extreme weather events, which are increasingly linked to human-induced climate change, already cause billions of dollars every year in property damage, loss of life, or forced relocation of vulnerable populations.[11] These effects are explored in greater detail in the next section on what risks are.

An important dynamic of climate change effects is that any one mechanism by which climate change creates risk, such as those listed above, although potentially devastating on a local to regional scale, might not rise to the level of a global catastrophe or an existential risk. For example, the Fifth National Climate Assessment (NCA5) reports on past U.S. climate-related catastrophes and assesses the risk of future catastrophes, particularly those associated with extreme weather events.[12] Furthermore, NCA5 highlights climate change as an existential threat to the culture and heritage of human populations, particularly for tribal communities and those with a close attachment to land or place. Although such place- or population-specific effects are often the basis by which researchers and civil society declare a climate crisis, individually they do not scale to a global catastrophe. However, the totality of effects from a series of climate-related disasters across the globe could either directly rise to this level with physical damage and loss of life or indirectly do so through strains on the Earth system such that even low-severity perturbations to the system push things over the edge. Additionally, cascades can occur in tightly coupled biological and socioeconomic systems,[13] potentially resulting in nonlinear effects. It is important to understand the risk that climate change poses to any one sector individually, but assessing these risks individually might be insufficient for characterizing the risks to interacting systems and sectors. This highlights the need for risk assessments to take a multisector view. Moreover, researchers have extensively studied complex systems spanning several disciplines and have shown that the behavior of these complex systems can be unpredictable and that the nature of these interactions are often revealed only once the system is perturbed.[14]

Thresholds for Abrupt and Severe Climate Change

Although the aforementioned pathways identify general mechanisms by which changes in the climate system can generate adverse consequences for human society, neither the research nor policy community has developed a consistent definition of the point at which climate change or its consequences constitute global catastrophic or existential risk.[15] Different communities apply different standards and lines of evidence. In this section, we summarize contemporary rationales underpinning concerns about the global catastrophic and even existential risk from climate change.

First, a broad variety of studies in at least the past two decades have investigated what are commonly referred to as *key risks* associated with climate change, which the IPCC defines as "as a potentially severe risk and therefore especially relevant to the interpretation of dangerous anthropogenic interference (DAI) with the climate system."[16] These include risks to low-lying coastal systems; terrestrial and ocean ecosystems; critical physical infrastructure; living standards; human health; food and water security; and peace and human mobility. Similarly, the concept of planetary boundaries has been used in the past decade to identify

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[10] IPCC, "Summary for Policymakers," 2022; Reidmiller et al., *Impacts, Risks, and Adaptation in the United States.*

[11] Newman and Noy, "The Global Costs of Extreme Weather That Are Attributable to Climate Change."

[12] Jay et al., "Overview."

[13] Lawrence, Blackett, and Cradock-Henry, "Cascading Climate Change Impacts and Implications."

[14] Clarke et al., "Sector Interactions, Multiple Stressors, and Complex Systems."

[15] Huggel et al., "The Existential Risk Space of Climate Change."

[16] O'Neill et al., "Key Risks Across Sectors and Regions," p. 2450.

conditions of the Earth system under which humans have evolved and thrived.[17] They include the climate system itself, as well as biodiversity, freshwater availability, cycling of nitrogen and phosphorus, acidification of the oceans, stratospheric ozone depletion, and atmospheric aerosols. Collectively, key risks and planetary boundaries dictate the health of ecosystems and their services that support human prosperity (e.g., agriculture and forestry, access to water, stable climate). Several of these boundaries have reportedly already been exceeded.[18] In addition to these planetary boundaries, various climate indicators have been used as proxy measures of rapid or catastrophic climate change: high temperature extremes and heat waves; tropical cyclone activity; sea-ice extent; wildfires; and drought.[19] Because the fate of these Earth-system elements has significant downstream implications for human populations, these elements' disruption, collapse, or failure is treated as a proxy for dangerous or catastrophic consequences.

Another perspective on definitions of rapid and extreme climate change are those global warming thresholds policymakers agree represent critical thresholds. For example, the international policy community has long used the concept of DAI as a benchmark for guiding efforts to reduce GHG emissions. That benchmark is grounded, but not defined, in Article 2 of the 1992 United Nations Framework Convention on Climate Change (UNFCCC). International scientific assessments have concluded that an increase in global mean temperature of more than 1.5 to 2.0°C (2.7 to 3.6°F) relative to preindustrial temperatures is the threshold for dangerous climate change. Hence, the 2015 Paris Agreement commits countries to limiting warming to well below 2°C and to aiming for 1.5°C. Warming beyond this threshold is assumed to result in large and widespread consequences for the Earth system.[20] Therefore, exceeding 1.5°C is often used as a proxy for global catastrophic or even existential risk. However, there is significant uncertainty about how such magnitudes of warming would result in catastrophic or existential risk to humanity.[21] The IPCC's special report, *Global Warming of 1.5°C*, for example, does not identify climate change as an existential risk to humanity.[22] Similarly, in the IPCC's Sixth Assessment Report, such terms as *existential* and *catastrophic risk* are used in the context of specific geographies, such as small island states, or vulnerable species or populations.[23]

A third perspective on catastrophic climate risk comes from a broader civil discourse that reflects the public's concerns about the potential implications of climate change. For example, U.S. polling data suggest that people in the United States are increasingly concerned about climate change and supportive of more-aggressive actions to reduce the risk.[24] A strong, international activist movement now exists that engages in advocacy for addressing climate change. That movement emphasizes the urgency of climate change; sponsors civic engagement efforts, including protest and civil disobedience, particularly among youths around the globe;[25] and argues that climate change is a potential existential risk. Social movements emerge from awareness of the science of climate change and the current state of progress on reducing climate risk. However, the bases for such social movements are also grounded in moral and ethical arguments and reflect the subjective

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[17] Lade et al., "Human Impacts on Planetary Boundaries Amplified by Earth System Interactions"; Rockström et al., "Planetary Boundaries"; Steffen et al., "Planetary Boundaries."

[18] IPCC, "Summary for Policymakers," 2022.

[19] FEMA, *FEMA Response and Recovery Climate Change Planning Guidance*.

[20] IPCC, "Summary for Policymakers," 2018.

[21] Huggel et al., "The Existential Risk Space of Climate Change."

[22] Masson-Delmotte et al., *Global Warming of 1.5°C*.

[23] Masson-Delmotte et al., *Climate Change 2021*.

[24] Pasquini et al., *Why Some Americans Do Not See Urgency on Climate Change*.

[25] Sisco et al., "Global Climate Marches Sharply Raise Attention to Climate Change"; Welch and Yates, "The Practices of Collective Action."

values and worldviews of those who participate.[26] Therefore, although social movements reflect a genuine and legitimate concern about climate change's potential risks to society, they are not necessarily grounded in objective assessment of those risks.

Probabilities of Rapid and Severe Climate Change

What would be required for such large-scale effects to be realized, and how likely are those conditions to develop? The latest projections of future climate change are based on a set of emission scenarios that result in different levels of radiative forcing. Those scenarios imply different economic development and technology pathways, as well as different levels of global investment in GHG-emission reductions. Those projections suggest that the world is not on track to limit warming to less than 2.0°C, much less 1.5°C. That level of warming is likely to be realized as early as the 2030s.[27] Despite the focus on 1.5 to 2.0°C as a key global warming threshold, greater magnitudes of global warming are possible and, given the current state of emission reductions, even probable (Table 7.2).

Some scenarios project warming of up to 2.5°C (4.5°F) by 2050 and 4 to 5°C (7.2 to 9.0°F) by 2100.[28] These increases imply much larger effects, including up to 1 m (39 inches) of sea-level rise by 2100. Nevertheless, even at these more-extreme magnitudes of climate change, it is not clear that these constitute global catastrophic or existential risks. At present, global GHG emissions are tracking along a trajectory that would imply warming on the order of 2 to 3°C by 2100, making such worst-case scenarios unlikely, particularly by 2050.[29]

Any one or any combination of four developments would have to transpire to drive greater magnitudes of climate change in the 21st century (Table 7.3). First, a resurgence in GHG emissions would have to reverse progress made in the past decade, particularly in wealthy countries. Specifically, this could involve expanded use of coal, which has seen a significant contraction in North America and Europe, combined with continued exploitation of natural gas resources. This would cause emissions to accelerate in the next few decades.

TABLE 7.2
Global Mean Temperature Thresholds

Threshold, in Degrees Celsius	Probability in the 21st Century, as a Percentage
<1.5	0
1.5–2.0	7
2.0–2.5	37
2.5–3.0	36
3.0–4.0	19
>4.0	1

SOURCE: Features information from United Nations Environment Programme, *The Closing Window*.

NOTE: Probabilities represent the likelihood of future global mean temperature change in the 21st century being within each range based on current climate mitigation policies and commitments under the Paris Agreement. More-ambitious actions to reduce emissions could significantly shift the probability distribution toward fewer degrees of change.

[26] Schipper et al., "Climate Resilient Development Pathways."

[27] IPCC, "Summary for Policymakers," 2021.

[28] IPCC, "Summary for Policymakers," 2021.

[29] IPCC, "Summary for Policymakers," 2021.

TABLE 7.3
Scientifically Plausible Drivers of Severe Climate Change in the 21st Century

Driver	Description
Acceleration of emissions	GHG emissions would have to resurge rapidly, particularly in developed countries.
High climate sensitivity	Positive climate feedback includes that associated with water vapor and the carbon cycle, which can result in climate sensitivity being much greater than assumed.
Low system thresholds	High sensitivity of critical social, biological, or economic systems could be due in part to limited capacity to cope with or adapt to climate risks.
Cascading and compounding effects	Cumulative effects of multiple effects, such as sea-level rise, extreme heat, drought, and flooding, and their downstream consequences (e.g., food insecurity, political conflict, and destabilization) contribute to degradation of human and ecological well-being.

Second, the climate would have to be more sensitive to GHG emissions than currently estimated from models and observations. Climate sensitivity is often expressed as the magnitude of global warming that would be realized from a doubling of the preindustrial atmospheric concentration of GHGs. The best estimate of climate sensitivity is 3.0°C.[30] However, there is a wide range of uncertainty around this estimate, resulting in a long tail of potential sensitivity that goes higher than 5°C. That higher sensitivity could contribute to large magnitudes of climate change even for more-modest emissions.

Third, social, ecological, and economic thresholds would have to be exceeded despite the efforts to manage and adapt to climate change. An inability for agricultural production to be managed in the face of high rates of climate change, insufficient freshwater resources to meet human demand despite conservation efforts, and rates of sea-level rise greater than humans can retreat from the coastline would all be examples of potential limits to adaptation.[31]

Fourth, although some of the direct effects of climate change can be readily anticipated based on understanding of projected magnitudes of climate change and systems' sensitivity to those changes, many effects can be difficult to predict or even anticipate. In particular, climate change has the potential to cause consequences that arise indirectly through cascading effects that propagate among sectors or communities.[32] For example, much of the concern about climate change's contributions to national security challenges or conflict arise from the cascading effects of drought, disasters, and other climate-related effects on human security, migration, and resource scarcity.[33] Similarly, the degradation and loss of ecosystems and related services (including agriculture, fisheries, and forestry) can destabilize communities and entire regions.[34] In addition to such indirect consequences, the compounded hazard of multiple effects occurring simultaneously can yield greater damage than a single effect in isolation.[35] Compounded hazard can undermine the ability to manage risk, thereby increasing the likelihood adverse effects. Collectively, cascading and compounded hazards act to increase the risk of catastrophic outcomes. However, their complexity makes them difficult to pre-

[30] IPCC, "Summary for Policymakers," 2021.

[31] Dow et al., "Limits to Adaptation."

[32] Clarke et al., "Sector Interactions, Multiple Stressors, and Complex Systems."

[33] National Intelligence Council, *National Intelligence Estimate*; Office of the Under Secretary for Policy, *Department of Defense Climate Risk Analysis*; Under Secretary of Defense for Policy, *National Security Implications of Climate-Related Risks and a Changing Climate*; U.S. Department of Defense (DoD), *Quadrennial Defense Review*.

[34] Guerry et al., "Natural Capital and Ecosystem Services Informing Decisions"; Nguyen et al., "Security Risks from Climate Change and Environmental Degradation."

[35] Clarke et al., "Sector Interactions, Multiple Stressors, and Complex Systems."

dict or for anyone to assign likelihood to potential outcomes. Hence, although cascading and compounded hazards could pose global catastrophic or existential risk, a lack of understanding of the pathways by which such consequences would arise contributes to significantly more uncertainty than when assessing the more-direct and -discrete effects of climate change.

In addition to the likelihoods of exceeding global average temperature thresholds, the likelihood of catastrophic climate change is also informed by the probabilities of exceeding specific thresholds for key risks (see Table 7.4 for examples). For example, irreversible melting of the Greenland or Antarctic ice sheet would reshape coastlines around the world, permanently inundating existing population centers where economic activity is concentrated. The simultaneous loss of multiple breadbasket regions that produce much of the world's staple crops could significantly undermine global food security, particularly if those effects were sustained over multiple years. Existing literature is consistent in reporting the plausibility of such scenarios but

TABLE 7.4

Probabilities of Key Risks in the Earth System

Key Hazard	Probability, as a Percentage	Note	Method
Greenland ice sheet	Moderate-warming scenario: 15–90; high-warming scenario: 60–100[a]	Probability estimates for the disintegration of the Greenland ice sheet by 2100	Expert elicitation
	Moderate-warming scenario: 0–75; high-warming scenario: 80–90[b]	Probability estimates for exceeding global mean temperature change thresholds (1.6°C[c] or 3.1°C[d]) consistent with an irreversible loss of the Greenland ice sheet	Physical modeling
West Antarctic ice-sheet collapse[e]	5–100	Probability of irreversible melting or collapse within 200 years, resulting in rapid sea-level rise. This range includes different assumptions about global mean temperature thresholds for irreversible loss and likelihoods of different warming scenarios.	Physical modeling
Multiple-breadbasket failure[f]	0.25–50	Annual probability of collapse under current global climatic conditions for different breadbasket regions and crops (e.g., wheat, soybean, maize, and rice)	Biophysical modeling
Amazon collapse[a]	Moderate-warming scenario: 5–95; high-warming scenario: 30–100	Probability estimates for collapse of the Amazon rainforest ecosystem by 2100	Expert elicitation
Shift of ENSO[a]	Moderate-warming scenario: 0–40; high-warming scenario: 1–70	Probability estimates for a significant shift in ENSO behavior by 2100	Expert elicitation
Mesoamerican Reef collapse[a]	Within 50 years: 0–23; within 100 years: 0–74	Probabilities of collapse based on scenarios applied to the next 100 years	Biophysical modeling

NOTE: In the probability column, M = moderate-warming scenario and H = high-warming scenario. Probability estimates are from the sources listed in the corresponding table notes and are based on multiple methods, as shown in the "Method" column. Most reflect a broad range of probabilities because inherent uncertainties, differences of opinions among experts, selected methods, and assumptions made in probability assessment.

[a] Kriegler et al., "Imprecise Probability Assessment of Tipping Points in the Climate System."

[b] Slingo et al., "Latest Scientific Evidence for Observed and Projected Climate Change."

[c] Robinson, Calov, and Ganopolski, "Multistability and Critical Thresholds of the Greenland Ice Sheet."

[d] Gregory and Huybrechts, "Ice-Sheet Contributions to Future Sea-Level Change."

[e] Pattyn and Morlighem, "The Uncertain Future of the Antarctic Ice Sheet"; Pattyn et al., "The Greenland and Antarctic Ice Sheets Under 1.5°C Global Warming"; Vaughan and Spouge, "Risk Estimation of Collapse of the West Antarctic Ice Sheet."

[f] Gaupp et al., "Changing Risks of Simultaneous Global Breadbasket Failure"; Masters, "Food System Shock."

reflects significant uncertainty about their likelihoods.[36] This uncertainty is attributed to multiple sources, including the method of probability assessment (e.g., biological or physical modeling versus expert elicitation), estimates of the sensitivity of key risks to global warming, and the use of different climate scenarios to estimate effects. However, Table 7.4 also indicates that the probabilities of exceeding thresholds for key risks are relatively high. In almost every example in Table 7.4, the low end of the probability range is greater than 1 percent; in most cases, the upper end of the probability range exceeds 50 percent, particularly for large magnitudes of warming and long time horizons.

Probabilities have generally increased, rather than decreased, in response to scientific advances over time. Although some of these outcomes (e.g., melting of ice sheets) have direct implications for global catastrophic risk, the consequences of other key risks (e.g., shifts in patterns of ocean circulation, such as ENSO) are less certain because their consequences would manifest indirectly through effects on other systems.

What Is the Risk from Rapid and Severe Climate Change?

Consequences: Mortality

An extensive body of literature has documented the observed effects that climate variability and change have on human health and includes projections of future health consequences of a changing climate under different global warming scenarios. The first of these papers emerged in the late 1980s and warned of catastrophic and existential risks.[37] These risks generally arise from direct pathways, such as exposure to extreme weather events, including extreme heat, flooding, and severe storms. However, climate change also indirectly affects human health through, for example, changes in the geography of disease vectors, effects on food and water security, or weather-related accidents.[38] Although the risks of climate change to human health are often cited as part of the climate emergency, rates of human injury and death associated with extreme weather events have generally gone down over time.[39]

Overall, society's capacity to cope with threats to health is anticipated to continue to rise, particularly within vulnerable countries, provided sufficient investments are made in adaptation, resilience, and economic development. Nevertheless, health modeling suggests that climate change will contribute to increases in mortality in the years ahead. One of the first global estimates of the health effects of climate change came from WHO in 2014. The authors estimated an additional 250,000 excess deaths per year by midcentury caused by climate change.[40] More-recent projections, also by WHO, suggest climate change–related deaths

[36] Gaupp et al., "Changing Risks of Simultaneous Global Breadbasket Failure"; Gregory and Huybrechts, "Ice-Sheet Contributions to Future Sea-Level Change"; Kriegler et al., "Imprecise Probability Assessment of Tipping Points in the Climate System"; Masters, "Food System Shock"; Pattyn and Morlighem, "The Uncertain Future of the Antarctic Ice Sheet"; Pattyn et al., "The Greenland and Antarctic Ice Sheets Under 1.5°C Global Warming"; Robinson, Calov, and Ganopolski, "Multistability and Critical Thresholds of the Greenland Ice Sheet"; Slingo et al., "Latest Scientific Evidence for Observed and Projected Climate Change"; Vaughan and Spouge, "Risk Estimation of Collapse of the West Antarctic Ice Sheet."

[37] Butler, "Climate Change, Health and Existential Risks to Civilization."

[38] Weatherdon et al., "Observed and Projected Impacts of Climate Change on Marine Fisheries, Aquaculture, Coastal Tourism, and Human Health."

[39] Cissé et al., "Health, Wellbeing, and the Changing Structure of Communities"; Global Burden of Diseases, Injuries, and Risk Factors Study 2019 Diseases and Injuries Collaborators, "Global Burden of 369 Diseases and Injuries in 204 Countries and Territories, 1990–2019"; Goklany, "Deaths and Death Rates from Extreme Weather Events."

[40] Kovats, Hales, and Lloyd, "Introduction and Key Findings."

of 529,000 per year by 2050, with an upper confidence limit of 736,000.[41] These mortality effects and broader health effects of climate change could also contribute to reductions in life expectancy.[42]

What is clear is that heat waves are the leading cause of weather-related mortality in the United States, with past heat waves associated with significant excess deaths and mass-casualty events. As a result, increases in the heat-related death rate are projected to outweigh decreases in cold-related deaths, particularly in response to a high-emission scenario.[43] Recent studies suggest that, if the global mean temperature increase reaches 4°C, large regions of the world could become uninhabitable because of heat stress unless significant adaptations are made.[44]

Although there is no accepted determination of what would constitute a global catastrophic health risk from climate change, authors of at least one report defined it as a mass-mortality event taking the equivalent of 25 percent of the population.[45] For the United States, based on the 2020 population (330 million), 25 percent would mean approximately 80 million people, or 2 billion for the estimated global population in 2022 of 8 billion.[46] The thresholds would be higher if one accounted for future population growth, estimated to be almost 370 million in the United States and 9.7 billion globally by 2050.[47] Mortality of this magnitude would effectively be ten times that of the 1918 influenza pandemic.[48] These values suggest a very high bar for catastrophic risk. However, by comparison, in 2019, an estimated 14 million people globally died from infectious diseases alone.[49] This baseline mortality is not generally considered catastrophic, despite much of that mortality being preventable. No published study has suggested the possibility of a singular mass-mortality event of this magnitude, nor is there evidence of an indirect mechanism, such as collapse of global food supplies or climate-mediated pathogenesis, that would result in such high rates of mortality. Even with cumulative losses over a century, mortality would not meet these thresholds.

Consequences: Ecosystem Instability

The degradation and loss of global ecosystems is a major effect associated with climate change. Significant changes have already been observed in the structure, function, and geographic distribution of plant and animal species around the world.[50] Changes in temperature and precipitation will expose existing ecosystems to climatic conditions that are significantly different from those in which the system evolved.[51] For ocean ecosystems, ocean acidification caused by rising atmospheric concentrations of CO_2 poses an additional

[41] Springmann et al., "Global and Regional Health Effects of Future Food Production Under Climate Change."

[42] Hauer and Santos-Lozada, "Inaction on Climate Change Projected to Reduce European Life Expectancy"; Roy, "A Panel Data Study on the Effect of Climate Change on Life Expectancy."

[43] Weinberger et al., "Projected Temperature-Related Deaths in Ten Large U.S. Metropolitan Areas Under Different Change Scenarios."

[44] Vecellio et al., "Greatly Enhanced Risk to Humans as a Consequence of Empirically Determined Lower Moist Heat Stress Tolerance."

[45] Kemp et al., "Climate Endgame."

[46] United Nations, "Population."

[47] Crown, *The Demographic Outlook*; Population Division, "World Population Prospects 2022."

[48] Taubenberger and Morens, "1918 Influenza."

[49] Gray and Sharara, "Global and Regional Sepsis and Infectious Syndrome Mortality in 2019."

[50] Li et al., "Vulnerability of the Global Terrestrial Ecosystems to Climate Change"; Pörtner et al., *Scientific Outcome of the IPBES–IPCC Co-Sponsored Workshop on Biodiversity and Climate Change*; Seddon, "Sensitivity of Global Terrestrial Ecosystems to Climate Variability."

[51] Beaumont et al., "Impacts of Climate Change on the World's Most Exceptional Ecoregions."

threat.[52] Key ecosystems at risk include the Amazon River basin, which is at risk of conversion from tropical rainforest to grassland, the Arctic tundra, and coral reefs around the world (Table 7.5).[53] These ecosystem losses reflect a broader concern about mass extinction and loss of biodiversity.[54] The risks become particularly high beyond 2.0°C.[55]

Ecosystem disruption can have significant downstream consequences for valuable services on which people depend, including agricultural and forestry products, water resources, nutrient cycling, and cultural values. Climate change's effects on these services are difficult to predict but are an important consideration in the assessment of catastrophic risk.[56] For example, 99 percent of coral reefs are projected to be lost if cli-

TABLE 7.5
Major Ecosystems at Risk from Climate Change

Ecosystem	Climate Driver of Risk	Socioeconomic and Ecological Effect of Ecosystem Disruption
Amazon rainforest[a]	• Increased temperatures • Reduced cloud cover and rainfall • Changes in hydrology	• More vector-borne diseases, such as malaria and dengue • More outbreaks of infectious diseases, such as cholera and meningitis
Boreal forests[b]	• Increased temperatures • Increases in wildfire risk • Poleward retreat of forest range	• Species decline • Invasive species and pests • Permafrost thawing • More fires • Change from carbon sink to carbon source
Coral reefs[c]	• Ocean warming • Widespread coral bleaching and dieback • Ocean acidification	• Decline in food provision and disruption of fisheries • Loss of livelihood opportunities • Decline in carbon sequestration • Loss of storm protection
Mountain ecosystems[d]	• Increasing risk of hazards, including landslides and glacial lake outburst flood events	• Effects on irrigation urbanization and industrialization and on hydropower generation
Arctic tundra[e]	• Increased release of CO_2 • Increased plant productivity	• Food insecurity • Reduced safety

[a] Garrett et al., "Forests and Sustainable Development in the Brazilian Amazon."

[b] Reich et al., "Even Modest Climate Change May Lead to Major Transitions in Boreal Forests."

[c] Colt and Knapp, "Economic Effects of an Ocean Acidification Catastrophe"; Eddy et al., "Global Decline in Capacity of Coral Reefs to Provide Ecosystem Services"; Hoegh-Guldberg et al., "Coral Reef Ecosystems Under Climate Change and Ocean Acidification"; Obura et al., "Vulnerability to Collapse of Coral Reef Ecosystems in the Western Indian Ocean"; Pörtner et al., *Scientific Outcome of the IPBES–IPCC Co-Sponsored Workshop on Biodiversity and Climate Change*; Spalding and Brown, "Warm-Water Coral Reefs and Climate Change."

[d] Lamprecht et al., "Climate Change Leads to Accelerated Transformation of High-Elevation Vegetation in the Central Alps"; Schirpke et al., "Future Impacts of Changing Land-Use and Climate on Ecosystem Services of Mountain Grassland and Their Resistance."

[e] Berner et al., "Summer Warming Explains Widespread but Not Uniform Greening in the Arctic Tundra Biome."

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52 Colt and Knapp, "Economic Effects of an Ocean Acidification Catastrophe"; Doney et al., "The Impacts of Ocean Acidification on Marine Ecosystems and Reliant Human Communities."

53 Scholze et al., "A Climate-Change Risk Analysis for World Ecosystems."

54 Maclean and Wilson, "Recent Ecological Responses to Climate Change Support Predictions of High Extinction Risk"; Thomas et al., "Extinction Risk from Climate Change"; Urban, "Accelerating Extinction Risk from Climate Change."

55 IPCC, "Summary for Policymakers," 2021.

56 Clarke et al., "Sector Interactions, Multiple Stressors, and Complex Systems."

mate change exceeds 1.5°C.[57] Although the loss of coral reefs is not a direct catastrophic risk to humans, the indirect dependence that specific communities and local economies have on coral reefs for livelihoods could result in significant damage. Similarly, the eastern Bering Sea snow crab population declined abruptly by more than 10 billion in three years, from 2018 to 2021.[58] Scientists found that the snow crab population crash was a result of starvation caused by a series of marine heat waves in the preceding years, which increased the species' caloric requirements. This, in combination with a historically high abundance of crab and a restricted range, created competition for a limited food source and ultimately led to this high-mortality event. The fishery, valued at roughly $150 million annually, was closed for the 2022 season—a devastating economic effect on the local, largely indigenous community, which relies heavily on landing taxes from the fishery. In two years, the community's tax revenues declined from approximately $2.5 million to around $200,000.[59]

Consequences: Societal Instability

An extensive literature documents climate change's risks to physical infrastructure, as well as the broader economy. Recent economic studies suggest that climate change has already resulted in significant economic losses. For example, the emissions attributed to global oil production between 1988 and 2015 alone are estimated to have already caused $50 billion to $200 billion in cumulative global economic damage by 2020.[60] A recent comparison of dozens of studies of the macroeconomic effects of climate change used global welfare as a common metric of economic effect. In other words, they studied the relative change in household income in response to a change in global average temperature (Figure 7.2).[61] These studies reflect the anticipated exponential growth in risk in response to greater magnitudes of climate change but suggest that effects are modest (less than a 10-percent reduction in household income) for warming up to 5°C, and only a few estimates are available for warming above 5°C.

Similarly, projections of future climate change–related effects on GDP vary because of differences in methods. Most suggest GDP decreases in the United States and globally on the order of 1 to 2 percent by 2100.[62] Given economic growth, global GDP will be on the order of $400 trillion by that time,[63] which translates into $4 trillion to $8 trillion per year in 2100 in damage. Although substantial in absolute terms, this is equivalent to only a few years of future GDP growth, so the world's GDP would still be 3.5 times higher than it was in 2023, despite these economic effects.

Nevertheless, recent years have seen several studies producing more-pessimistic projections of future GDP effects, which is a function of attempts to capture a broader array of consequences and learning about the sensitivity that human and natural systems have to climate. For example, researchers in some recent eco-

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57 Hoegh-Guldberg et al., "Securing a Long-Term Future for Coral Reefs."

58 Szuwalski et al., "The Collapse of Eastern Bering Sea Snow Crab."

59 Lewis, "How Warming Ruined a Crab Fishery and Hurt an Alaskan Town."

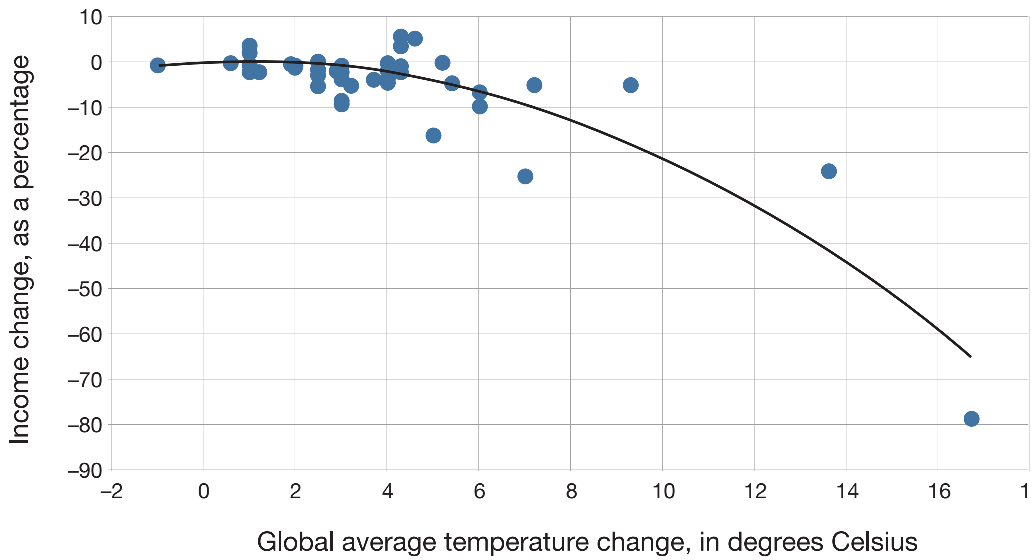
60 Burke et al., *Quantifying Climate Change Loss and Damage Consistent with a Social Cost of Greenhouse Gases*; Rickels, Meier, and Quaas, "The Historical Social Cost of Fossil and Industrial CO_2 Emissions."

61 Tol, "A Meta-Analysis of the Total Economic Impact of Climate Change."

62 Council of Economic Advisers and Office of Management and Budget, *Methodologies and Considerations for Integrating the Physical and Transition Risks of Climate Change into Macroeconomic Forecasting for the President's Budget*; Newell, Prest, and Sexton, "The GDP–Temperature Relationship."

63 According to Organisation for Economic Co-operation and Development (OECD), "Real GDP Long-Term Forecast." We extended to 2100 the OECD's projections to 2060 by assuming a constant annual rate of growth of 1.4 percent beyond 2060, which is equivalent to the rate of growth assumed in the OECD's projections for 2057 to 2060. Hence, the projected value of GDP of $237.8 trillion in 2060 increases to $414.8 trillion by 2100. GDP in 2023 was an estimated $116.6 trillion.

FIGURE 7.2
Climate Change's Effect on Global Welfare



NOTE: The blue circles represent comparative estimates of the effect that climate change since preindustrial times has had on global welfare, using a variety of estimation methods. The gray line represents welfare's generalized functional response to temperature change.

nomic studies have projected effects on the order of 10 to 20 percent of GDP in 2100, and some have suggested effects of more than 50 percent of GDP.[64] These estimates are an order of magnitude higher than traditional assumptions, suggesting effects of $40 trillion per year by the end of the century. Effects of this scale imply weak economic growth (averaging less than 1 percent per year) for the remainder of the 21st century and a large social cost of climate change. Such weak growth while the population of the world is rising suggests negative effects on poverty, consumption, and quality of life. For example, although the implied scale of GDP by the end of the century is higher than that of 2023, given a population of approximately 10 billion as soon as 2050,[65] GDP per capita could be lower than it is today. These global effects would be disproportionately larger in low-income and vulnerable countries. For example, some studies suggest effects on the order of 33 percent of developing-nation GDP, even if warming is limited to 1.5°C, and as high as 64 percent for 2 to 3°C of warming.[66] The status of economic development is highly correlated with state fragility, as well as a country's contributions to global GHG emissions.

A significant fraction of the economic damage associated with climate change is effects on infrastructure and the built environment—including direct damage to infrastructure from extreme weather events, which drives repair, replacement, and maintenance, as well as associated loss-of-use costs associated with infrastructure degradation. This damage to infrastructure affects such factors as the costs and reliability of travel, water and power, and access to other services. In some instances, these costs will be transient (e.g., storm damage to a physical asset), but they can also be persistent because of repetitive events or the perma-

[64] Burke, Hsiang, and Miguel, "Global Non-Linear Effect of Temperature on Economic Production"; Burke et al., *Quantifying Climate Change Loss and Damage Consistent with a Social Cost of Greenhouse Gases*; Kikstra et al., "The Social Cost of Carbon Dioxide Under Climate-Economy Feedbacks and Temperature Variability"; Newell, Prest, and Sexton, "The GDP–Temperature Relationship."

[65] Population Division, *World Population Prospects 2022*.

[66] Andrijevic and Ware, *Lost and Damaged*.

nent loss of an asset or opportunity (because, for instance, of sea-level rise and permanent inundation of an asset). Key risks would be associated with the loss of natural resources needed to support an infrastructure service (e.g., decline of water resources), effects on long-lived infrastructure that was designed or sited during a different climate era, and infrastructure that is poorly designed and hardened against climate and weather and is therefore particularly vulnerable to failure. Until recently, most infrastructure systems were designed to withstand historical climate variability and not designed to account for future climate change. However, public- and private-sector actors are taking action to shift infrastructure design practices to account for future climate change and to include additional safety factors to hedge against uncertainty. In addition, most physical infrastructure is highly distributed and even decentralized, making it difficult for climate change effects to scale to a global catastrophe.

Climate change effects on the built environment could be accompanied by effects on governance systems and social institutions. Such erosion of institutions could arise from multiple sources. One of the most-immediate challenges is the instability arising from climate change effects or countries' responses to those effects. For example, the projections of economic costs of climate change effects suggest the potential for significant slowing of future economic growth. This translates into both public and private institutions' ability to maintain budgets to invest in public and private goods and services.[67] Moreover, global efforts to mitigate climate change effects through energy transitions could have additional effects in resource-dependent economies that rely on fossil fuel revenue for economic stability. For example, a synthesis of modeling studies indicates that aggressive reductions in GHG emissions to manage climate risk could also slow global economic growth and countries' ability to address other social and economic challenges.[68]

Various experts have argued that measures of climate change's direct effects on the economy underestimate the broader downstream consequences for human society and the natural environment.[69] For example, social unrest could arise from civil society's concerns about the risks of climate change and the ability of governments and other institutions to adequately manage those risks. In many countries, climate change is now a mainstream policy issue and, as a result, a litmus test for policymakers. Responses to climate change shape political platforms and campaigns, as well as the leadership of corporations, raising the possibility of climate change being one element of a justification for regime change.[70] Hence, a civil protest movement is growing around climate change that is using civil disobedience as a mechanism for driving more-aggressive climate policies.[71] This is likely to be more significant in places where institutions are unable to provide people with necessities, such as food, water, and energy security. These tend to be low-income countries that are already fragile.[72] At the same time, many countries' efforts to advance climate actions to reduce the risks of climate change have encountered public backlash. For example, public protests in France, Italy, Argentina, and Germany have occurred in response to increased costs of transportation, food, and energy, as well as the retirement of fossil fuel assets and industry.[73]

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[67] Dolan et al., *The Budgetary Effects of Climate Change and Their Potential Influence on Legislation*; Eriksen et al., "Adaptation Interventions and Their Effect on Vulnerability in Developing Countries."

[68] Schipper et al., "Climate Resilient Development Pathways."

[69] DeFries et al., *The Missing Economic Risks in Assessments of Climate Change Impacts*.

[70] Leipprand and Flachsland, "Regime Destabilization in Energy Transitions."

[71] Schipper et al., "Climate Resilient Development Pathways."

[72] Figueiredo Pereira de Faria, "Understanding How Climate Change Impacts Food Security and Human Development in the Fragile States"; Schipper et al., "Climate Resilient Development Pathways."

[73] Leipprand and Flachsland, "Regime Destabilization in Energy Transitions"; Schipper et al., "Climate Resilient Development Pathways."

Another potentially destabilizing force on global institutions is the increasing use of the courts as a vehicle for shaping climate action. One report indicates that the magnitude of climate litigation doubled between 2017 and 2023, with such costs now distributed across 55 countries.[74] This could include proregulatory litigation against governments or the private sector for not taking sufficient action on climate change or antiregulatory litigation for actions that are deemed too costly or have negative effects on individual freedoms and civil rights.[75]

Although this discussion identifies various pathways by which climate change could undermine societal stability, understanding of how such effects would translate into broader fragility or collapse of nation-states remains quite limited. Thresholds for these societal systems, such as the point at which failure for a government to satisfy societal needs results in collapse of the government, are largely unknown and likely only partially influenced by changes in the climate system.

Consequences: Reduced Human Capabilities

Climate change has been named as one of the greatest threats to human health in the 21st century.[76] It is already undermining key social determinants of human physical and psychological well-being, such as access to basic needs (e.g., food, water, stable housing) and social support institutions (e.g., health care), human security and freedom, and health equity. The direct and indirect physical and mental effects of natural disasters are well documented in the literature dating back to at least the 1980s.[77] Examples of direct effects include illness, injury, or death resulting from extreme weather events, as well as other effects, such as reduced work productivity. Indirectly, changes to environmental conditions and extreme weather events can lead to poor air quality (e.g., wildfire smoke) and respiratory illness; waterborne diseases and other water-related health effects; zoonoses, vector-borne diseases, malnutrition, and foodborne diseases; noncommunicable diseases; and mental and psychosocial health.[78]

Although evidence unequivocally shows that climate change affects human health, accurately measuring the scale and magnitude of these effects is challenging. Individual and community vulnerability and the ability to adapt to a changing environment are at the heart of this dilemma. Moreover, understanding how these effects on health outcomes affect well-being is equally challenging because the term *well-being* is used to describe a diverse, and sometimes contradictory, set of concepts—what constitutes an effect on well-being could differ by culture and context.[79] Direct elements of well-being, such as access to basic needs (e.g., food, water, and stable housing), are easier to measure than indirect elements, such as the symbolic or cultural components of identity.

Nevertheless, identifying and measuring climate change's effect on quality of life or well-being is a growing area of research. Discussions in the literature center on a few concepts, including effects on the pillars of

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[74] Burger and Tigre, *Global Climate Litigation Report*.

[75] Furniss et al., *Assessing the Vulnerability of Watersheds to Climate Change*; McCormick et al., "Strategies in and Outcomes of Climate Change Litigation in the United States."

[76] Costello et al., "Managing the Health Effects of Climate Change."

[77] Hrabok, Delorme, and Agyapong, "Threats to Mental Health and Well-Being Associated with Climate Change."

[78] Barreau et al., "Physical, Mental, and Financial Impacts from Drought in Two California Counties, 2015"; Caminade, McIntyre, and Jones, "Impact of Recent and Future Climate Change on Vector-Borne Diseases"; Gronlund et al., "Vulnerability to Renal, Heat and Respiratory Hospitalizations During Extreme Heat Among U.S. Elderly"; Kjellstrom and McMichael, "Climate Change Threats to Population Health and Well-Being"; Lake, "Food-Borne Disease and Climate Change in the United Kingdom"; McMichael et al., *Climate Change and Human Health*.

[79] Huggel et al., "The Existential Risk Space of Climate Change"; Lamb and Steinberger, "Human Well-Being and Climate Change Mitigation."

living standards that undermine acceptable levels of well-being, implications for human security and freedom, and climate anxiety and effects on mental health.[80] The concepts of human security and freedom are a broad framing that arguably encompasses the other two concepts. Effects on living standards that undermine well-being are discussed in literature that has examined the links between climate change and higher costs of living, including effects on agriculture and related food shortages, infrastructure damage and supply chain disruptions, and the implications of slower economic growth.[81]

Most of the research on climate change and mental health has been conducted in high-income countries, which has implications for generalizability across global populations. However, the evidence strongly suggests a negative association between climate-related exposure and mental health, including posttraumatic stress disorder, anxiety, depression, psychiatric hospitalizations, and increased suicide rates.[82] There is also a small but growing body of literature on climate change's effects on indigenous populations' mental health, particularly from the perspective of sense of place and identity.[83] There is evidence to suggest that these populations are among those who are most acutely experiencing effects on mental health from climate change.[84] Culturally, many indigenous communities define themselves by their environments. In this sense, climate change could pose an existential threat to these populations if their environments become uninhabitable or traditional ways of life are no longer viable.

The geographic extent and duration of the effect on human well-being depend on the nature of the climate stressor and the dimension of well-being of concern. Additionally, because several drivers of good health and well-being interact with one another, effects could cascade and compound among these drivers, extending the acute effects of a precipitating event much longer than expected. With extreme weather, some effects on human health and well-being, such as acute stress and posttraumatic stress disorder, can be felt immediately during or after the event but can also be felt for years after the event. Researchers in one study found that stress, anxiety, and fear persisted for at least three years after a flood event.[85] In the longer term, depression and suicidal ideation can develop.[86] For slower-moving climate stressors, such as sea-level rise, for which the full extent of the physical effects might not be felt for years, anxiety associated with the awareness of climate change and the perception of risk might serve as a proxy for understanding these stressors' implications for mental health.[87]

Evidence shows that geographically vulnerable and socially disadvantaged populations disproportionately experience effects on human health and well-being stemming from climate change and that other risk

[80] See, for example, Adger, "Climate Change, Human Well-Being and Insecurity"; Charlson et al., "Climate Change and Mental Health"; Hrabok, Delorme, and Agyapong, "Threats to Mental Health and Well-Being Associated with Climate Change"; Huggel et al., "The Existential Risk Space of Climate Change"; and Soutar and Wand, "Understanding the Spectrum of Anxiety Responses to Climate Change."

[81] Ghadge, Wurtmann, and Seuring, "Managing Climate Change Risks in Global Supply Chains"; Nelson et al., *Climate Change*; Newman and Noy, "The Global Costs of Extreme Weather That Are Attributable to Climate Change"; Schipper et al., "Climate Resilient Development Pathways."

[82] Charlson et al., "Climate Change and Mental Health"; Hrabok, Delorme, and Agyapong, "Threats to Mental Health and Well-Being Associated with Climate Change."

[83] Middleton et al., "Indigenous Mental Health in a Changing Climate."

[84] Middleton et al., "Indigenous Mental Health in a Changing Climate."

[85] Jermacane et al., "The English National Cohort Study of Flooding and Health."

[86] Dumont et al., "Climate Change and Risk of Completed Suicide"; Hrabok, Delorme, and Agyapong, "Threats to Mental Health and Well-Being Associated with Climate Change."

[87] Coffey et al., "Understanding Eco-Anxiety"; Soutar and Wand, "Understanding the Spectrum of Anxiety Responses to Climate Change."

factors, including socioeconomic status, gender, and existing conditions, play a key role.[88] Because climate change acts as a multiplier on individuals' and communities' existing conditions, one can expect to see these trends continue without intervention. Individuals' and communities' ability to cope with the mental health effects of climate change is uncertain. Very few empirical studies have examined these coping mechanisms or the efficacy and scalability of interventions and policies aimed at addressing mental health effects.[89]

How the Risk from Extreme Climate Change Will Change in the Next Decade

The scientific literature is quite clear that the risks associated with extreme climate change will continue to grow for at least the first half of the 21st century, independently of efforts made to reduce global GHG emissions. This is due to a certain magnitude of lock-in in terms of future GHG emissions, as well as time lags between emissions and associated changes in the climate system. Because CO_2 can remain in the atmosphere for thousands of years, past GHG emissions have committed Earth to some degree of future warming. If emissions were to cease, the global temperature would quickly stabilize.[90] However, emissions would take decades to return to their preindustrial levels. Meanwhile, some elements of the climate system, such as ice sheets, sea levels, or the temperatures of the deep ocean, would respond much more slowly.[91] Therefore, the consequences of climate change are anticipated to become more severe in the next decade, and studies suggest that the rates of global mean temperature change and sea-level rise are accelerating.[92]

Nevertheless, even under the most-extreme scenarios of climate change, large-scale temperature shifts in the Earth system are not anticipated until toward the end of the 21st century. This suggests a low probability of global catastrophic or existential risk in the next decade. Projected trajectories of warming by 2050 are relatively similar among quite disparate assumptions about rates of GHG emissions and feedback loops, resulting in warming on the order of 2 to 3°C by midcentury given current progress on GHG-emission reductions. Nevertheless, that level of warming exceeds the commonly used DAI threshold of 1.5 to 2.0°C, as well as thresholds for various key risks and tipping points in the Earth system (Table 7.4). As a result, there is a moderate to high probability of catastrophic or existential risk during that time on a local to regional basis for some particularly vulnerable populations or communities. Projections of truly global catastrophic or existential risks by 2050 are unlikely, according to existing studies. That said, some scientists are warning that warming of 2 to 3°C by midcentury could commit the world to catastrophic risks later in the century because of such warming's implications for positive feedback, such as ice-sheet melting, and release of additional GHGs from the thawing of Arctic permafrost (Table 7.4).[93] Also, climate change could trigger other types of risk. For example, the thawing of permafrost and melting of glaciers could expose human populations to novel pathogens, suggesting a pathway for pandemic risk (see Chapter 6).[94] Therefore, even if climate

[88] Hrabok, Delorme, and Agyapong, "Threats to Mental Health and Well-Being Associated with Climate Change"; Kjellstrom and McMichael, "Climate Change Threats to Population Health and Well-Being"; Middleton et al., "Indigenous Mental Health in a Changing Climate."

[89] Charlson et al., "Climate Change and Mental Health."

[90] Palazzo Corner et al., "The Zero Emissions Commitment and Climate Stabilization."

[91] Palazzo Corner et al., "The Zero Emissions Commitment and Climate Stabilization."

[92] Dangendorf et al., "Persistent Acceleration in Global Sea-Level Rise Since the 1960s"; Hansen et al., "Global Warming in the Pipeline."

[93] Spratt and Dunlop, *Existential Climate-Related Security Risk*; Xu and Ramanathan, "Well Below 2 °C."

[94] Miner et al., "Emergent Biogeochemical Risks from Arctic Permafrost Degradation"; Wu et al., "Permafrost as a Potential Pathogen Reservoir."

conditions in 2050 were not consistent with humans experiencing a global catastrophic or existential risk, the conditions could place the Earth system on such a pathway, directly or indirectly.

Much of the more-severe outcomes of climate change would manifest toward the end of the 21st century. Uncertainty in climate policy and future GHG emissions create large uncertainty in projections of climate change and sea-level rise by 2100 and beyond, including global warming more than 4 to 5°C under high-emission scenarios. Although such scenarios appear increasingly unlikely, the scientific community has failed to reach consensus on their plausibility. Warming of this magnitude would likelier than not trigger most of the Earth-system key risks listed in Table 7.4. However, there are large uncertainties associated with the downstream consequences of such key risks for human society and well-being.

What Has Been and Could Be Done to Manage Risk from Extreme Climate Change?

Table 7.6 describes options for mitigating risk from extreme climate change. Two broad strategies exist for addressing the risks that climate change poses. Both give people significant agency and opportunity for risk management. Yet, both are also associated with significant social, technological, and financial constraints that affect their feasibility to be effectively deployed at scale in practice. One is climate mitigation, which includes actions to reduce the rate and magnitude of changes in the climate system. The most common mitigation strategy to reduce GHG emissions. Since 1992, the international community has been working to reduce emissions through the UNFCCC. The UNFCCC has generated two international agreements: the 1997 Kyoto Protocol, which proved unsuccessful, and the 2015 Paris Agreement, which is currently in force. Under the Paris Agreement, signatories agree to GHG-reduction targets and then work to implement policies and technologies consistently with meeting those targets. Studies in the past decade have demonstrated that limiting warming to less than 1.5 to 2.0°C can substantially reduce, but not eliminate, the projected risks associated with climate change.

It is possible that climate mitigation would be achieved through geoengineering approaches that remove CO_2 from the atmosphere through human interventions, including

- enhancing natural processes that uptake CO_2 in the land (tree planting) or oceans (ocean fertilization)
- industrial techniques that capture CO_2 from concentrated sources, such as power plants, or directly from the atmosphere.

TABLE 7.6

Climate Change: Overview of Risk Mitigation Opportunities

Mitigation Dimension	Mitigation Option
Reduce the likelihood of occurrence.	• Exercise one or more of the extensive technological, regulatory, and behavioral options to monitor and slow the accumulation of greenhouse gases in the atmosphere.
Disrupt the mechanisms leading to risk.	• Exercise one or more experimental geoengineering options to offset radiative forcing and remove or sequester carbon dioxide.
Reduce the severity of effects.	• Exercise one or more of the extensive technological, regulatory, and behavioral options to avoid, reduce, or spread the risks that climate change poses to society; their deployment capacity varies.
Enhance response and recovery.	• Scale up existing response and recovery options to mitigate societal risks.

Research also is being conducted on other forms of geoengineering—specifically, solar radiation modification, which has the potential to reduce atmospheric radiative forcing and, by extension, global warming and climate change, by reflecting solar energy away from Earth. However, solar radiation modification also has the potential to generate its own climatic and environmental risks, so its costs and benefits must be weighed against those of climate change.[95]

Although climate mitigation alters the magnitude of changes in the climate system, risk can also be managed by reducing climate change's effects on human populations and natural ecosystems.[96] This is generally referred to as enhancing resilience to climate change or as adapting to the changing climate to avoid or reduce consequences or capitalize on potential opportunities. This can be achieved by reducing societal exposure to climate hazards and reducing those systems' sensitivity to climate. Examples include shifting locations of assets and people to reduce exposure, increasing tolerance thresholds, hardening infrastructure, and implementing nature-based solutions. For example, advances in genomics can enhance the agricultural crops' productivity and drought tolerance to offset climate change effects or combat agricultural pests and diseases.[97] Such efforts are often closely aligned with best practices for hazard mitigation and emergency management. There is significant opportunity to deploy such strategies to manage climate risk, provided that adequate resources and planning are allocated. However, as noted in Table 7.3, the capacity to adapt to climate change is finite for both natural and human systems. Therefore, the rate and magnitude of climate change can exceed the capacity to adapt,[98] particularly in low-resource and disadvantaged communities or countries.

Summary

Decades of scientific investigation convey high confidence that human-induced changes in the climate system, largely associated with past and future emissions of GHGs, are already having significant adverse effects on the environment and, by extension, human well-being. These effects are projected to continue to manifest across a range of geographic scales (local to global) and economic sectors. Effects will grow in frequency, intensity, and duration in response to increases in future global average temperature. However, what constitutes a global catastrophic risk in the context of climate change is poorly defined and contested. Scientific studies to date indicate a low, but not zero, probability that the magnitudes of climate change currently projected to occur by 2050 or 2100 constitute a global threat to civilization or continued human existence. However, catastrophic outcomes and even existential losses of some human populations, ecosystems, and biodiversity at local to regional scales are likely, particularly in the absence of risk management interventions.

From the assessment presented in this chapter, we see four key pathways by which climate change could trigger global catastrophe:

- rapid acceleration in the use of fossil fuel production and use: This could make more-pessimistic scenarios of future emissions likelier, thus increasing the likelihood of Earth reaching magnitudes of global warming consistent with more-catastrophic outcomes.

[95] Honegger, Michaelowa, and Pan, "Potential Implications of Solar Radiation Modification for Achievement of the Sustainable Development Goals"; MacMartin et al., "Scenarios for Modeling Solar Radiation Modification."

[96] FEMA, *FEMA Response and Recovery Climate Change Planning Guidance*; IPCC, "Summary for Policymakers," 2022.

[97] Pourkheirandish et al., "Global Role of Crop Genomics in the Face of Climate Change"; Scheben, Yuan, and Edwards, "Advances in Genomics for Adapting Crops to Climate Change."

[98] Dow et al., "Limits to Adaptation."

- the Earth system's increased sensitivity to changes in climate: Although current estimates put the world on track for 2 to 3°C of warming by 2100 under current policy trajectories, positive feedback could push the world to higher levels of warming.
- reductions in thresholds for key risks in the Earth system: In the event that large-scale discontinuities in the Earth system, such as the collapse of ice sheets or major ecosystems, are triggered by lower magnitudes of warming than currently estimated, the risk of global catastrophic outcomes would increase.
- cascading and compounded risks: Climate change's ability to trigger complex consequences that are not captured in existing, reductionist studies could result in surprise catastrophic events or contribute to other types of existential threats, such as global pandemics.

Although all of these pathways are plausible scenarios, they are either unlikely based on existing evidence (e.g., rapid acceleration in the use of fossil fuel use) or highly uncertain because of scientific limitations (e.g., the consequences of cascading risk). Ongoing monitoring of the evolution of climate change and its consequences is therefore important for understanding the potential for catastrophic risk. Moreover, a broad assortment of mechanisms exists for climate risk management. Yet the capacity to deploy those mechanisms in a timely and equitable manner at the scale at which they are needed is also part of the uncertainty associated with climate change risk assessment.

CHAPTER 8

Nuclear War: Summary of Risk

Nuclear weapons harness the energy of nuclear fission and fusion reactions to produce extremely powerful explosions (e.g., equivalent to the detonation of tens of thousands of tons of TNT). Such explosions produce both prompt and delayed effects that can harm individual people, essential infrastructure, and large-scale ecosystems. Since the introduction of nuclear weapons in 1945, many have perceived large-scale use of these weapons in war as a key global catastrophic risk that could imperil the viability of human civilization. Table 8.1 lists risks, by risk dimension, for nuclear war.[1]

Because of intense government, military, and scientific interest since the 1940s, nuclear war might be among the best-understood global catastrophic risks, although large-scale uncertainties persist. Different uses of nuclear weapons in different numbers and locations can be expected to produce significant direct and indirect effects. The future probability of nuclear war and its likely effects is hard to predict because of the wholly anthropogenic nature of this threat. However, the degrading geopolitical situation and such developments as the expansion of China's nuclear arsenal suggest that the probability of nuclear war is likely to

TABLE 8.1
Nuclear War: Overview of Risk

Risk Dimension	Assessment for Nuclear War
Most-significant consequences	• Direct fatalities of hundreds of millions of people; possible indirect fatalities of billions • Destruction of economic value totaling hundreds of trillions of dollars • Destruction of governmental infrastructure • Severe ecological damage with a possibility of human extinction if nuclear weapons are designed and employed to cause this outcome
Factors that influence the magnitude of risk	• Number and power of nuclear weapons • How nuclear weapons are employed in war (e.g., against what targets)
Likelihood of risk	• Human decisionmakers influence the level of risk, so it can vary. • Estimates that a nuclear war will occur during this century vary from negligible to greater than 80%.
Temporal nature of the risk and change in the next decade	• Nuclear war might last only a few hours, but direct fatalities would continue to occur for weeks and indirect fatalities for years. • Major ecological disruption could continue for years, while some environmental effects could persist for millennia. • Because of breakdowns in international relations and increases in the sizes of potential belligerents' nuclear arsenals, the risk of nuclear war appears to be increasing.
Quality of the evidence supporting the assessment	• The direct effects of nuclear weapons are relatively well understood. • Indirect effects are less predictable but better studied than those of many other global catastrophic risks.

[1] This chapter addresses only nuclear war. Accidental use would detonate only one or a few weapons unless it led to a response, which would then be nuclear war. Terrorists would not have access to arsenals large enough to cause the effects discussed in this chapter.

increase in the coming decade. The consequences of nuclear war could be mitigated by such means as civil defense and arms control. Fortunately, even though nuclear war poses a global catastrophic risk, scientific consensus suggests that it is unlikely to cause human extinction unless belligerents intentionally pursue that goal.

What Is Known About the Causes of Risk from Nuclear War?

How Nuclear Weapons Cause Damage

A nuclear explosion within Earth's atmosphere results in several direct effects, including blast, thermal impulse, gamma and neutron radiation, and radioactive fallout:

- Blast effects cause damage via both static overpressure, which has a crushing effect on buildings and other structures, and dynamic pressure, which is the pressure from the blast wind and has a tearing effect.[2]
- The thermal impulse consists of blackbody radiation emitted by the volume of gas heated by the nuclear burst (the fireball). For a burst of multimegaton yield, this impulse can last many seconds. The thermal impulse poses a risk of acute burn injuries to unprotected humans and large-scale fire ignitions that can result in firestorms under enabling conditions.[3]
- Gamma and neutron radiation constitutes only a small percentage of the energy released by a typical nuclear weapon, but it can also be extremely hazardous to exposed organisms. These forms of radiation are produced directly by the nuclear burst and can penetrate through light forms of shielding, including that provided by typical buildings.
- Residual radiation or radioactive fallout, by contrast, is a hazard that occurs in the aftermath of a nuclear burst. A nuclear explosion releases fission products (lighter nuclei resulting from the fission of uranium or plutonium atoms) and activation products (radioactive isotopes resulting from the absorption of neutrons). These can then fall out from the atmosphere and injure organisms via external or internal radiation exposure. A thermonuclear weapon detonated in contact with the ground can result in fallout hazards lethal to unshielded humans over an area of many thousands of square miles (i.e., the area of a small state or country). Although the acute threat from radioactive fallout is at its maximum in the hours and days after a nuclear burst, certain long-lived radioactive isotopes, such as strontium-90, can continue to pose biological and environmental hazards for decades or longer.[4]

The largest nuclear weapons developed by the United States and the Soviet Union during the Cold War nuclear arms race had megaton yields.[5] In theory, thermonuclear weapons can be built with far greater yields than those tested in the 1950s and 1960s, although no state is known to have pursued such bombs.

Where Nuclear Weapons Detonate Matters

Nuclear explosions outside the atmosphere can result in considerably different hazards from those described above because the atmosphere lacks matter near the detonating device and because radiation in the atmo-

2 Needham, *Blast Waves*.

3 Glasstone and Dolan, *The Effects of Nuclear Weapons*.

4 Izraėl', *Radioactive Fallout After Nuclear Explosions and Accidents*.

5 Glasstone and Dolan, *The Effects of Nuclear Weapons*.

sphere interacts with Earth's magnetic field. These effects of nuclear explosions in the magnetosphere include the Argus effect, in which beta particles released by the burst travel along Earth's magnetic field lines, potentially damaging satellites.[6] Neither an underground nor underwater burst results in a luminous fireball, and the mass of ground or water absorbs the gamma and neutron radiation from an explosion. An underground nuclear burst can produce a large crater, as well as powerful ground shock effects that can destroy subterranean structures.[7] Shallow underwater nuclear explosions produce a plume instead of the familiar mushroom cloud associated with terrestrial explosions.[8]

The most-famous effects of high-altitude nuclear bursts are various forms of electromagnetic pulse (EMP). High-altitude EMP consists of several distinct phenomena that occur over different timescales, but each of them results in an EMP (essentially, a radio signal) experienced at Earth's surface. Like radioactive fallout, a high-altitude EMP can cause effects over very large areas, depending on the altitude of the burst—in some cases, spanning continent-wide areas. These forms of EMP pose scant direct risk to biological organisms but could cause severe damage to various kinds of technology and infrastructure. High-frequency EMP, for example, could damage microelectronics, while magnetohydrodynamic EMP primarily threatens electric power distribution systems.

Some Nuclear Weapons Can Be Specialized

The effects described above can all result from the detonation of nuclear weapons typical of the designs of those that have been built historically. Specialized nuclear weapons adapted to produce different effects have also been proposed and developed. The most famous of these is the neutron bomb, which is designed to release a much larger fraction of its yield as high-energy neutrons than a typical nuclear weapon does. Because the atmosphere attenuates neutrons, the enhanced radiation effects of the neutron bomb can affect only a relatively small area, so nuclear powers have adopted these weapons only for niche applications.

Another type of specialized nuclear weapon that no nuclear state is known to have deployed is the salted bomb. These hypothetical weapons would be designed to harness the ample neutrons released by thermonuclear reactions to produce extremely large quantities of activation products that would then result in extremely long-lived radioactive fallout.[9] In 1965, a RAND analyst argued that salted weapons, such as cobalt bombs, were not a practical engineering possibility.[10]

Nuclear War Could Lead to Nuclear Winter

Although a single detonation of a large nuclear weapon in a densely populated area could result in millions of direct fatalities, a substantial nuclear war could be expected to consist of hundreds or thousands of nuclear explosions. The secondary effects of the detonation of this number of nuclear weapons might result in more injuries and fatalities than the initial nuclear exchange. Since the late 1940s, a variety of mechanisms have been suggested by which a nuclear war could cause catastrophic effects for countries not involved in the initial hostilities. Although scientific investigation ultimately showed that most of these mechanisms were either impossible or improbable, some of them still pose considerable concern.[11]

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6 Glasstone and Dolan, *The Effects of Nuclear Weapons*.

7 Glasstone and Dolan, *The Effects of Nuclear Weapons*.

8 Dombrovskii, Filippovskii, and Iakovlev, ["General Picture of the Development of the Explosion"].

9 Arnold, "The Hydrogen–Cobalt Bomb."

10 Brode, *A Survey of the Weapons and Hazards Which May Face the People of the United States in Wartime*.

11 Scouras, *Nuclear War as a Global Catastrophic Risk*.

In recent decades, the primary mechanism by which scientists anticipate that nuclear war might pose global hazards is nuclear winter—climatological changes caused by aerosols released into the atmosphere resulting from nuclear detonations. Depending on the amount of aerosol introduced into the atmosphere, its optical properties, and the altitudes at which the aerosol is deposited in the atmosphere, even a relatively limited nuclear war could have dramatic climatological effects.[12] The primary means by which recent analyses of nuclear winter have indicated that this aerosol would be produced and introduced into the atmosphere is by pyroconvective columns associated with urban firestorms caused by nuclear attacks on cities. Computer modeling suggests that such columns might inject smoke into the upper troposphere or even directly into the stratosphere.[13] Solar energy could loft dark aerosols, which absorb energy, in the upper troposphere into the stratosphere. Depending on the aerosol and conditions, stratospheric aerosols might have extremely long residence times, so even a relatively limited amount of stratospheric aerosol could have an outsize, long-lasting climatological effect. The resulting decline in surface temperatures would depend on the amount and optical properties of the stratospheric aerosol. Scientists disagree about what constitute plausible assumptions about these two variables. Several analyses assuming that the aerosol consists of finely divided black carbon (BC) showed that a small nuclear war, such as a regional conflict between India and Pakistan, could cause a global drop in temperatures and rainfall that could, in turn, result in serious agricultural disruption over large areas of the globe.[14]

Nuclear War Is Unlikely to Pose a Risk of Human Extinction

Although the invention of the atomic bomb led to fears that nuclear war might pose an existential threat to humans based on concerns about radiation exposure and consequent genetic mutations, advances in scientific understanding of genetics and biological experiments during the 1950s established that these fears were greatly exaggerated.[15] More enduring was the fear that global radiological contamination from thermonuclear explosions might be sufficient to cause human extinction. The best available evidence, however, suggests that the equivalent of a truly immense nuclear arsenal—orders of magnitude larger than the stockpiles that existed at the height of the Cold War arms race—would be necessary to produce this sort of outcome.[16]

Nuclear winter has also been proposed as a source of existential risk from nuclear weapons,[17] but the current scientific literature does not support the view that climatological effects from nuclear war would be sufficient to cause human extinction. For example, if every city in the world with at least 10 million inhabitants were struck with 50 15-kiloton weapons, worst-case estimates of stratospheric BC injection would be less than 165 teragrams (Tg) rising above the tropopause to drive long-term climate effects.[18] This is far less

[12] Toon et al., "Rapidly Expanding Nuclear Arsenals in Pakistan and India Portend Regional and Global Catastrophe."

[13] Wagman et al., "Examining the Climate Effects of a Regional Nuclear Weapons Exchange Using a Multiscale Atmospheric Modeling Approach."

[14] Xia et al., "Global Food Insecurity and Famine from Reduced Crop, Marine Fishery and Livestock Production Due to Climate Disruption from Nuclear War Soot Injection."

[15] Glass, "The Biology of Nuclear War."

[16] Some philosophical accounts of post- and transhumanism are not discussed here. Some key texts include Bostrom, "What Is Transhumanism?" and essays in More and Vita-More, *The Transhumanist Reader*.

[17] Turco et al., "Nuclear Winter."

[18] Lyons et al., "Organic Matter from the Chicxulub Crater Exacerbated the K–Pg Impact Winter." Compare that with Population Division, *The World's Cities in 2016*, for the number of megacities (those with more than 10 million inhabitants; in 2016, there were 31 such cities in the world); and Toon et al., "Atmospheric Effects and Societal Consequences of Regional Scale Nuclear Conflicts and Acts of Individual Nuclear Terrorism," for the amount of BC generated by each megacity (as much as 5.22 Tg). The 165-Tg bound on BC assumes an 80- to 100-percent rate of stratospheric injection. With more-conservative

than the 750 to 2,500 Tg of stratospheric BC associated with the asteroid impact that caused the Cretaceous–Paleogene extinction 66 million years ago.[19] Leading nuclear winter researcher Alan Robock concluded that, after a severe nuclear winter, "[y]ou wouldn't have any civilization, so it's a horrible thing to contemplate, but we probably couldn't make ourselves go extinct that way."[20]

Barring the discovery of some unpredicted mechanism vastly increasing the expected lethality of nuclear war, it does not appear that any plausible use of either historical or current arsenals could result in human extinction. It would be a mistake, however, to conclude that nuclear weapons could not cause human extinction under any circumstances. Instead, it appears that nuclear weapons would have to be designed and used with the explicit goal of killing all humans to produce this result. Nuclear strategist Herman Kahn suggested that it might be possible to build a "doomsday machine," a weapon designed with the explicit goal of causing human extinction if it were to be used. Kahn argued that such a weapon was a real physical possibility and suggested that, under some circumstances, a government might attempt to create one.[21] It is conceivable, but unlikely, that future nuclear stockpiles will be much larger than those that existed during the Cold War or that an arsenal designed explicitly to threaten human extinction will be created.

What Is the Risk from Nuclear War?

Nuclear war is unique in that governments openly and explicitly threaten to impose this catastrophic risk on their adversaries as an instrument of policy. Plausible uses of nuclear weapons could result in hundreds of millions of fatalities within a few days or weeks, the total collapse of governments, the loss of industrial facilities and infrastructure supporting modern economies in targeted countries, and environmental and ecological disruptions that could last years or decades. A large-scale nuclear war might cause all these disastrous consequences simultaneously; even a very limited nuclear war could cause one or more of them.

Every nuclear power claims that the purpose of its nuclear arsenal is to deter potential adversaries by posing credible threats of inflicting "unacceptable damage" on them in retaliation for nuclear attack or other unacceptable provocation.[22] The various nuclear weapon states differ in how they threaten to use nuclear weapons to harm their adversaries, however. The United States has said that it plans to employ nuclear weapons only in ways that are consistent with international humanitarian law and the law of armed conflict.[23] This suggests that U.S. nuclear war plans are to avoid harming civilians or civilian infrastructure when possible while still seeking to attain military objectives. Other nuclear states, by contrast, have indicated that threatening to use their nuclear weapons in the most destructive manner possible in case of war is the best means of deterring such a conflict in the first place. For example, lesser nuclear powers with arsenals totaling

estimates on the injection rate, such as the 6-percent rate in Reisner et al., "Climate Impact of a Regional Nuclear Weapons Exchange," less than 10 Tg of BC enters the stratosphere. One teragram is 10^{12} g.

19 Lyons, "Organic Matter from the Chicxulub Crater Exacerbated the K–Pg Impact Winter." Conversely, the upper-bound teragram amount for extinction-level nuclear winter is achieved under worst-case assumptions of BC generation and injection when every city with more than 1 million inhabitants is struck; however, it is implausible that every such city would satisfy the worst-case assumptions.

20 Ord, *The Precipice*, p. 336.

21 Kahn, *On Thermonuclear War*.

22 Burutin et al., "The Concept of Unacceptable Damage," p. 3.

23 DoD, *Report on the Nuclear Employment Strategy of the United States*.

a few dozen or hundred warheads, such as France and China during the Cold War, tend to plan to use those weapons to target their adversaries' key cities in the event of war.[24]

The destructiveness of a nuclear war would depend enormously on how the conflict was fought. Certain kinds of conceivable nuclear wars, such as a conflict in which nuclear weapons were used only in space or constrained to a small theater of operations, might directly cause few or no human fatalities. Even though attacks optimized against population centers would almost certainly kill far more civilians than most strikes against military targets, few militarily significant uses of nuclear weapons seem to avoid the prospect of serious harm to civilians. The discussion in this section assumes a conflict in which nuclear weapons are used in ways that cause significant numbers of civilian fatalities.

Consequences: Mortality

The results of the atomic bombings of Hiroshima and Nagasaki in 1945 demonstrate the extraordinary efficacy of nuclear weapons as a means of injuring and killing human beings. More-modern nuclear weapons and delivery systems promise to be considerably more effective for these purposes if they are employed with the goal of destroying populations. During the Cold War, damage-assessment models were developed to predict the number of fatalities and injuries that might result from a nuclear exchange.[25] These models often showed that an all-out nuclear exchange between the superpowers could be expected to cause hundreds of millions of prompt fatalities.[26] Even a relatively limited nuclear war could result in tens of millions of prompt fatalities.[27]

Although some nuclear attacks would be so lethal as to leave relatively few victims with nonfatal injuries, other uses of nuclear weapons could result in huge numbers of people with injuries who might recover if given timely and appropriate medical attention. Nuclear attacks intended to destroy military targets while reducing civilian fatalities could result in large numbers of injuries of this type, which could, in turn, become fatalities given the difficulty of provisioning adequate medical care in the aftermath of nuclear attack.[28]

Consequences: Societal Instability

Governance Disruption

Belligerents in a nuclear war are likely to attempt to disrupt their opponents' ability to govern their territories or to try to eliminate the adversary government altogether. Some strategists have argued that targeting adversary leaders personally is the best way to deter those leaders from nuclear attack, but others emphasize that, if adversary leadership is killed, there might be no one with whom to negotiate an end to hostilities.[29] Even if top leadership survives in hardened subterranean bunkers or mobile command posts, many essential personnel must not just remain alive but also be able to continue doing their jobs in the aftermath of nuclear attack if the government is to continue functioning.

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[24] Lewis, *The Minimum Means of Reprisal*.

[25] Hoeber, *Military Applications of Modeling*.

[26] For a summary of the results of some damage-assessment models, see Logan, "The Nuclear Balance Is What States Make of It."

[27] Daugherty, Levi, and von Hippel, "Casualties Due to the Blast, Heat, and Radioactive Fallout from Various Hypothetical Nuclear Attacks on the United States."

[28] Abrams, "Medical Supply and Demand in a Post–Nuclear-War World."

[29] Sagan, *Moving Targets*, pp. 84–89.

Economic and Infrastructure Destruction

Industry and infrastructure might be even more vulnerable to nuclear attack than human beings are. Nuclear war plans have emphasized the targeting of economic centers since the invention of nuclear weapons in 1945. In the mid-1960s, Alain Enthoven found in his analyses of "assured destruction" that the same 400-Mt retaliation strike that could be expected to destroy 25 percent of the Soviet population would also destroy 50 percent of the Soviet Union's industry (as estimated from factory floor space).[30] Without elaborate efforts to protect key economic resources from nuclear attack, such as building underground factories, it seems likely that nuclear attacks designed to prevent economic recovery would succeed, perhaps to a much greater degree than an attacker would expect. Even if many economic assets survive, the loss of essential infrastructure, such as transportation or key nodes, could make those that remain relatively useless.

Consequences: Ecosystem Instability

Scientists concur that nuclear war could cause worldwide damage to the global environment in ways that could cause catastrophic ecosystem disruptions for years (in the case of nuclear winter) with possible lower-level biological effects (such as genetic damage from carbon-14 in the environment) persisting for millennia. They disagree, however, about the likely scale, intensity, and duration of the ecosystem effects resulting from smaller nuclear wars.

In the mid-1970s, National Research Council analysts proposed a mechanism by which nuclear war could cause global environmental harm. Nitric oxide produced by thermonuclear bursts and lofted into the stratosphere could be expected to deplete the ozone layer, resulting in far greater exposure to UV rays at Earth's surface.[31] Since the mid-1980s, the primary environmental consequence of nuclear war of interest to scientists has been nuclear winter.[32]

In addition, some scientists have suggested that the different kinds of damage resulting from large-scale employment of thermonuclear weapons, such as fallout killing birds and mammals but not insects while fires destroy vegetation, would create deleterious synergies worse than the sum of their parts.[33] Analysts disagree about the extent to which possible systemic ecological disruptions should be a cause of alarm relative to the comparatively predictive individual harms that collectively cause them.

Reduced Human Capabilities

Given the numerous deleterious effects of nuclear war for governments, economies, and ecosystems, even a nuclear war that caused relatively few immediate casualties might result in a significantly reduced quality of life for survivors. Some analysts and officials over the decades have suggested that survivors of a thermonuclear attack would be reduced to a preindustrial form of civilization or even total barbarism. However, these types of social effects are difficult to predict and might not be particularly correlated with the number of weapons used.

Along with a precipitous drop in living standards caused by the enormous loss of wealth and industrial capacity, nuclear war could also be expected to cause long-lasting harms to human health by imposing not

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30 Enthoven and Smith, *How Much Is Enough?* The main discussion of assured destruction begins on page 174 of that book.

31 Committee to Study the Long-Term Worldwide Effects of Multiple Nuclear-Weapons Detonations, *Long-Term Worldwide Effects of Multiple Nuclear-Weapons Detonations*.

32 Scouras, *Nuclear War as a Global Catastrophic Risk*.

33 Special Subcommittee on Radiation, *Biological and Environmental Effects of Nuclear War.*

just physical but psychological trauma.[34] In addition to those injured or disabled in the initial nuclear attacks by such effects as blast and fire, radiological contamination might continue to impose costs, such as cancer, on future generations.[35]

Uncertainty and Timing of Risk from Nuclear War

Probabilistic Aspects of Nuclear Risk

Since the atomic bombings of Japan, analysts and pundits have sought to predict the probability that nuclear weapons will be used again in the future. Both expert and amateur intuitions about this question vary enormously, however, with expressed opinions varying from absolute confidence that nuclear weapons will not be used for the foreseeable future to total certainty that they will.[36] Mathematician Martin Hellman has argued that it is possible to apply probabilistic risk assessment techniques to assess the order of magnitude of the probability of nuclear war, which he has estimated to be around 1 percent per year (encompassing a range from 0.3 percent per year to 3 percent per year).[37] Table 8.2 provides a variety of recent estimates for the probability that nuclear weapon use will result in a global catastrophe or human extinction over the course of the next 100 years. The basic challenge of predicting the likelihood of nuclear catastrophe is that the uncertainties are both aleatory and epistemic. As the authors of a 2023 National Academies of Sciences, Engineering, and Medicine study concluded, "Past examples of nuclear war and nuclear terrorism are rare. As such, there is little direct evidence that can be relied upon to make empirical estimates about the probability of either."[38]

The estimates given in Table 8.2 reflect the general expert consensus that nuclear war is unlikely to cause the extinction of humans. However, important scientific uncertainties remain that need to be accounted for prior to dismissing nuclear war as a possible existential risk. The implausibility that nuclear war could cause human extinction hinges on the size of past and current nuclear arsenals. Rudimentary calculations suggest that arsenals larger than those that existed during the Cold War but still physically attainable could pose a credible threat of human extinction given known or predicted mechanisms by which nuclear war could threaten human survival. For example, in 1976, Massachusetts Institute of Technology (MIT) physicist Bernard Feld estimated that a nuclear explosion in contact with the ground producing 1 Mt of fission yield would result "in a lethal level of fallout . . . over an area of about 1,000 square miles (2,500 square kilometers)."[39]

This suggests that 60,000 such weapons would be sufficient to irradiate Earth's entire land area with local fallout to a sufficient degree that only well-sheltered people could be expected to survive.[40] The Cold War nuclear production complexes of the United States and the Soviet Union could have produced this number of nuclear weapons.[41] Feld also suggested, plausibly, that a nuclear war producing more than 1,000,000 Mt

[34] Katz, *Life After Nuclear War*.

[35] von Hippel, "The Long-Term Global Health Burden from Nuclear Weapon Test Explosions in the Atmosphere."

[36] Scouras, "Framing the Questions."

[37] Hellman and Cerf, "An Existential Discussion."

[38] Committee on Risk Analysis Methods for Nuclear War and Nuclear Terrorism, *Risk Analysis Methods for Nuclear War and Nuclear Terrorism*, p. 114.

[39] Feld, "The Consequences of Nuclear War," p. 11. Feld defined a lethal dose as 500 rads, equivalent to 5 grays in modern International System (Système international, or SI) units.

[40] Ord, *The Precipice*.

[41] Norris and Kristensen, "Global Nuclear Stockpiles, 1945–2006." The Federation of American Scientists estimated that world nuclear stockpiles peaked at a total of about 70,000 warheads in the late 1980s, although most of these weapons had yields of far less than 1 Mt.

TABLE 8.2
Probabilistic Estimates of the Catastrophic and Existential Risks of Nuclear War

Estimator	Outcome	Forecast, as a Percentage
Martin Hellman[a]	Probability of large-scale nuclear war per year	~1
	Probability of large-scale nuclear war by 2100	~54
Forecasting Research Institute domain experts[b]	Nuclear catastrophic risk by 2030	1
Forecasting Research Institute superforecasters[b]	Nuclear catastrophic risk by 2030	0.5
Forecasting Research Institute domain experts[b]	Nuclear catastrophic risk by 2050	3.4
Forecasting Research Institute superforecasters[b]	Nuclear catastrophic risk by 2050	0.83
Forecasting Research Institute domain experts[b]	Nuclear catastrophic risk by 2100	8
Forecasting Research Institute superforecasters[b]	Nuclear catastrophic risk by 2100	4
Forecasting Research Institute domain experts[b]	Nuclear extinction risk by 2100	0.55
Forecasting Research Institute superforecasters[b]	Nuclear extinction risk by 2100	0.074
Aird, "Database of Nuclear Risk Estimates"	Extrapolated median estimate of nuclear risk's contribution to total existential risk by 2100	1.58
Sandberg and Bostrom, *Global Catastrophic Risks Survey*	Human extinction risk caused by all nuclear wars before 2100	1
Toby Ord[c]	Existential catastrophe via nuclear war by 2120	0.01

NOTE: In some cases, such as Hellman, the estimator is a paper providing a single estimate. In the case of the Forecasting Research Institute, it provided estimates for multiple items from two groups of estimators:

[a] Hellman, "Probabilistic Risk Assessment."

[b] Karger et al., *Forecasting Existential Risks*.

[c] Ord, *The Precipice*.

of fission fallout would raise radiation exposures from global fallout to an average lethal dose.[42] Although sheltering and uneven distribution of fallout might still permit some people to survive after a radiological catastrophe of this scale, in principle, sufficient global fallout can cause human extinction—and the radiological doomsday machines about which Kahn speculated could be a practical possibility.[43] Nonetheless, it seems vanishingly improbable that such an outcome would ever result from the use of nuclear arsenals not intentionally designed to cause human extinction.

[42] Feld, "The Consequences of Nuclear War"; Glass, "The Biology of Nuclear War." In the early 1960s, it was assessed that the 92 Mt of fission fallout resulted in a whole-body dose of 98 millirems. Linear scaling suggested that global fallout from a large-scale superpower war releasing 10,000 Mt of fission fallout would result in an average dose in people of about 10 rem. Scaling this again by a factor of 50 to 500,000 Mt of fission fallout, as implied by Feld, shows a whole-body dose of about 500 rem (roughly 0.5 sieverts [Sv] in modern SI units).

[43] Wellerstein, "An Unearthly Spectacle." In 1954, Edward Teller proposed the development of a 10,000-Mt thermonuclear weapon. If such devices proved feasible, a few hundred of them could serve as the basis for Kahn's doomsday machine. See Wellerstein, "An Unearthly Spectacle."

Temporal Aspects of Nuclear Risk

Although the deleterious aftereffects of a nuclear war might extend far into the future, such a conflict could break out with little or no advance warning. Several nuclear-weapon states maintain their nuclear forces in a state in which they can be used within minutes of receiving a launch order, and more governments could adopt this kind of launch-on-warning or launch-under-attack posture in the future. Nuclear strategists distinguish between tactical and strategic warning. Tactical warning consists of indicators that a nuclear attack is currently in progress—for example, indicators from early-warning satellites and radars that missiles have been launched. Since the introduction of nuclear-armed ballistic missiles, it has appeared that tactical warning between the detection of an ongoing attack and when weapons begin reaching their targets will probably be no more than tens of minutes. Strategic warning, by contrast, consists of indicators that an adversary is preparing for a possible nuclear attack. Under fortuitous conditions, months or even years of strategic warning might be available.

Unfortunately, there is no guarantee that either strategic or tactical warning will be available. Nuclear attack might occur with no warning if an attacker smuggled nuclear weapons into its adversary's capital to decapitate the opposing government at the outset of hostilities, for example. Moreover, both tactical and strategic warning could be spurious because benign or circumstantial indicators can be misinterpreted.

Although a nuclear exchange might be over within a few hours, many of the resulting fatalities could be expected to occur days and weeks after the final weapon detonated. Fires might continue to rage for hours or days after the attack, and radioactive fallout could take even longer to decay to levels that no longer pose acute threats. Many types of injuries associated with nuclear attack, such as acute radiation poisoning from fallout, take weeks to reach actual death. Some computer simulations suggest that aerosols deposited in the upper atmosphere by a nuclear war could continue to cause significant global cooling for years.[44] Other effects of a large-scale nuclear war, such as long-lived radiological contamination, could continue to cause ecological disruption for decades or longer.[45]

How Will the Risk from Nuclear War Change in the Next Decade?

Because regrettable geopolitical trends, both the likelihood of nuclear war occurring and the potential destructiveness of such a war if it occurs appear likely to increase in the next decade. After decades of reductions, the total number of nuclear weapons in global stockpiles is now increasing. China, in particular, is expanding its nuclear arsenal and could become a peer of Russia and the United States in its nuclear capabilities in coming years. Russia's isolation following that country's invasion of Ukraine could lead Kremlin leaders to rely ever more heavily on their nuclear arsenal to compensate for economic and conventional military weakness. North Korea, meanwhile, is cultivating sophisticated nuclear capabilities, including thermonuclear weapons and road-mobile ICBMs, despite its poverty and technological backwardness. The arms control regime cultivated during and since the Cold War has now seriously eroded; after the scheduled expiration of the New START Treaty in 2026, there might be nothing to replace it.[46] China has shown no interest in participating in these types of arms control agreements. Although it is difficult to judge just how much these trends will exacerbate nuclear risks, it seems reasonable to expect that these risks will increase in a

[44] Toon et al., "Rapidly Expanding Nuclear Arsenals in Pakistan and India Portend Regional and Global Catastrophe"; Wagman et al., "Examining the Climate Effects of a Regional Nuclear Weapons Exchange Using a Multiscale Atmospheric Modeling Approach."

[45] Pittock et al., *Environmental Consequences of Nuclear War.*

[46] Treaty Between the United States of America and the Russian Federation on Measures for the Further Reduction and Limitation of Strategic Offensive Arms. The parties agreed to extend the treaty through February 4, 2026.

world with more nuclear weapons, less arms control, and greater geopolitical tensions than today. Technological trends could exacerbate these challenges. For example, several authors have argued that AI and other emerging technologies could undermine strategic stability between nuclear weapon states and increase the probability of nuclear war.[47]

What Has and Could Be Done to Manage Risk from Nuclear War?

Approaches to manage risk from nuclear war can be divided into two categories: those that seek to prevent a nuclear war and those that aim to reduce the destructiveness of nuclear war if it occurs. The first of these approaches is captured by the first mitigation dimension in Table 8.3, and the second is captured in the other three mitigation dimensions in the table. Although analysts generally agree that these two approaches are closely related to each other, the nature of this relationship has been extremely controversial since the invention of nuclear weapons. Some strategists intuit that the best way to prevent nuclear war is to increase the destruction it would cause, but others worry that this approach lacks credibility or that nuclear war might result from miscalculation or accident.[48]

The only way to ensure that nuclear weapons will not be used is to eliminate all of them. Since the atomic bombings of Japan, activists and statespeople have sought a satisfactory path to uninvent the bomb and prevent these weapons from being reintroduced. Language in the 1968 Non-Proliferation Treaty obligates its signatories, including the United States, to work toward the ultimate elimination of nuclear weapons.[49] The present-day iteration of these aspirations is the Treaty on the Prohibition of Nuclear Weapons, but no nuclear-weapon state has signed this agreement.

Nuclear weapon states and some of their allies argue that the purpose of their nuclear arsenals is to prevent nuclear war by deterring adversaries from starting one. The logic of nuclear deterrence can create incentives to make nuclear war worse if it occurs. Some argue that the best way to make deterrence credible is to embrace vulnerability and reject measures, such as civil defense, that seek to limit the destructiveness of nuclear war.[50] An alternative school of thought contends that the most-impressive military capabilities make for a more effective deterrent, so states should accumulate nuclear weapons to reduce the probability of

TABLE 8.3
Nuclear War: Overview of Risk Mitigation Opportunities

Mitigation Dimension	Mitigation Opportunity
Reduce the likelihood of occurrence.	• Reduce international tensions; reduce the number and power of nuclear weapons.
Disrupt the mechanisms leading to risk (prevent nuclear weapons from reaching their targets once launched).	• Engage counterforce for damage limitation and use active (air and missile) defenses.
Reduce the severity of effects (limit damage caused by weapons that detonate).	• Engage in civil defense (bomb shelters, evacuation, dispersal of potential targets).
Enhance response and recovery.	• Stockpile food and medical supplies; make continuity-of-government arrangements.

[47] Geist, *Deterrence Under Uncertainty*; Johnson, *AI and the Bomb*.

[48] Glaser, "Why Do Strategists Disagree About the Requirements of Strategic Nuclear Deterrence?"

[49] U.S. Arms Control and Disarmament Agency, *Arms Control and Disarmament Agreements*. The treaty's official title is Treaty on the Non-Proliferation of Nuclear Weapons.

[50] Glaser, *Analyzing Strategic Nuclear Policy*.

nuclear war.[51] Even if one of these intuitions is accurate, if the probability of nuclear war is nonzero, such a war can still be fought, and the resulting global catastrophe might prove to be much worse than it would have been had that intuition not been followed.

The goal of arms control is to reduce both the probability of nuclear war and its destructiveness if it occurs. Arms control agreements can help build trust between potential adversaries and reduce tensions between them. Arms control can also try to mitigate some of the destabilizing characteristics associated with nuclear weapons, such as first-strike incentives. It can also reduce the death and destruction resulting from nuclear war by reducing the number of weapons available to belligerents, as well as by shaping the characteristics of those weapons.[52]

Measures to limit damage from nuclear war if it occurs include offensive counterforce, active defenses, and passive defenses. Offensive counterforce consists of attacks, often nuclear, against an adversary's nuclear weapons to prevent those weapons from being used. Some analysts contend that this type of counterforce attack could be highly effective in the present technological environment, but critics contend that pursuing the requisite capabilities threatens to increase the probability of nuclear war to an unacceptable degree.[53] Active defenses, meanwhile, are designed to intercept attacking nuclear weapons after they are launched but before they reach their targets. Active defenses include missile defense systems and air-defense systems. Finally, passive defenses include such measures as shelters, evacuation, and dispersal to reduce the damage that a nuclear attack can cause to life and property.[54] Preparations to facilitate postattack recovery, such as stockpiling seed and essential capital goods, can be categorized as a form of passive defense.

Summary

Nuclear war poses a global catastrophic risk. A large-scale nuclear war could result in hundreds of millions of direct fatalities, a larger number of injured, and long-term health effects that could persist for generations. Environmental effects of nuclear war are less predictable but might exacerbate these human consequences considerably while wreaking havoc on the biosphere. Mercifully, current science suggests that nuclear war with existing or foreseeable nuclear arsenals is unlikely to result in human extinction. It appears technically and economically conceivable, however, that stockpiles and weapons capable of imperiling the survival of humans as a species could be created. Nuclear war is unique among global catastrophic risks in that states use the threat of nuclear attack as a means to prevent other states from starting a nuclear war. Because of worsening relations between nuclear weapon states and the prospective proliferation of nuclear weapons to additional states, the likelihood of nuclear war appears to be increasing at present. The probability of nuclear war can be reduced by reducing international tensions (e.g., via arms control and confidence-building measures). Unfortunately, means of reducing the likely scale of the damage resulting from nuclear conflict if it occurs appear to be costly and of uncertain efficacy. Such measures include counterforce attacks to destroy adversary nuclear weapons before they can be launched, active defenses to destroy adversary weapons between when they are launched and when they reach their targets, and passive defenses (e.g., bomb shelters) to protect people from those nuclear weapons that reach their targets.

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51 Kroenig, *The Logic of American Nuclear Strategy.*

52 For the classic text on this subject, see Schelling and Halperin, *Strategy and Arms Control.*

53 Glaser and Fetter, "Should the United States Reject MAD?"; Lieber and Press, "The New Era of Counterforce."

54 Dowling and Harrell, *Civil Defense.*

CHAPTER 9

Artificial Intelligence: Summary of Risk

The OECD has defined *AI system* as a machine-based system that, for explicit or implicit objectives, infers from the input it receives how to generate outputs (e.g., predictions, content, recommendations, or decisions that influence physical or virtual environments). As AI systems become more capable, as people place them in positions of increasing influence and control, and as competition drives developers and adopters to rush development and use, many are concerned about the intentional or accidental consequences of their deployment. Table 9.1 shows our assessment of AI risks.

AI—which encompasses a wide variety of technologies, techniques, and uses—has emerged as a transformative technology with the potential to revolutionize many aspects of society. AI has applications in many sectors, including health care, manufacturing, transportation, and defense. This diversity makes it difficult to generalize about AI because the risks and implications vary significantly depending on the specific use case. Nevertheless, we can define several potential factors that contribute to risk:

- AI can supply enabling information to malicious actors.
- AI systems are prone to specification and robustness failures.
- AI could open the door to adversarial attacks.
- AI errors can be difficult to detect and correct.

TABLE 9.1
Artificial Intelligence: Overview of Risk

Risk Dimension	Assessment for AI
Most-significant consequences	• AI amplifies existing catastrophic risks, including risks from nuclear war, pandemics, and climate change. • AI systems have the potential to destabilize social, governance, economic, and critical infrastructure systems, as well as potentially disempower people.
Factors that influence the magnitude of risk	• The extent to which malicious actors might use AI to advance their goals • The extent to which AI can influence critical systems in ways that are misaligned with human goals and bring about catastrophe
Likelihood of risk	• The likelihood of AI-enabled catastrophe is deeply uncertain and depends on human decisions about the safety and use of AI systems, as well as many other factors, such as those noted above.
Temporal nature of the risk and change in the next decade	• Risks associated with AI will continue to grow in the next decade as AI becomes more capable and more widely used.
Quality of the evidence supporting the assessment	• Little empirical evidence exists for assessing the likelihood or consequence of AI risk, and little rigorous modeling exists to provide theoretical evidence.

Ultimately, the risks that AI poses can be understood primarily as an amplification of existing risks both acute (e.g., nuclear war, pandemics, climate change) and slower-moving (e.g., disruption of social, governance, economic, and critical infrastructure systems; disempowerment of human decisionmaking). Mitigation strategies are twofold: designing safe systems and ensuring safe deployment and continued monitoring.

What Do We Mean by "Artificial Intelligence"?

Historically, *AI* referred primarily to "the *study* of the computations that make it possible to perceive, reason, and act."[1] Increasingly, the term is used to refer to *computer systems* that can perform tasks at or approaching the level of human capability. There is little consensus on a definition of such AI, with experts in various fields disagreeing on the scope of what the term *AI* should encompass. A widely accepted definition from the OECD describes an AI system as

> a machine-based system that, for explicit or implicit objectives, infers, from the input it receives, how to generate outputs such as predictions, content, recommendations, or decisions that can influence physical or virtual environments. Different AI systems vary in their levels of autonomy and adaptiveness after deployment.[2]

Early work in AI focused on applications that were good at specific tasks, such as driving a car, playing chess, or recognizing speech.[3] More recently, artificial neural networks and deep neural networks (DNNs) have created new and broader capabilities that have spurred the growing concern around AI safety. Artificial neural networks are inspired by biological neural circuits.[4] They are composed of nodes that communicate with other nodes via connections of varying weights. A DNN is a neural network of many layers.[5] These networks have exhibited success at complex tasks (e.g., image classification) and strategy games (e.g., Go).[6] LLMs, such as Bidirectional Encoder Representations from Transformers (BERT), Meta Llama, Generative Pretrained Transformer (GPT) 4, and PaLM are also examples of DNNs. The LLM is an example of a *foundation model*, a term coined by researchers to refer to large machine learning models trained on extensive amounts of data that are general in purpose and can be fine-tuned to perform a large variety of tasks that they have not been explicitly trained to do.[7]

Some believe that deep learning models are a significant step toward achieving artificial general intelligence (AGI).[8] AGI is not a well-defined concept, but the term *AGI* generally refers to AI systems that can "match or exceed human performance across a broad class of cognitive tasks," "handle problems quite differ-

[1] Winston, *Artificial Intelligence*. Emphasis is ours.

[2] OECD, "OECD AI Principles Overview."

[3] Russell and Norvig, *Artificial Intelligence*.

[4] Rosenblatt, "The Perceptron."

[5] Krizhevsky, Sutskever, and Hinton, "ImageNet Classification with Deep Convolutional Neural Networks"; Schmidhuber, "Deep Learning in Neural Networks."

[6] On image classification, see LeCun et al., "Gradient-Based Learning Applied to Document Recognition." On Go, see Silver et al., "Mastering the Game of Go with Deep Neural Networks and Tree Search."

[7] Bommasani et al., "On the Opportunities and Risks of Foundation Models"; Brown et al., "Language Models Are Few-Shot Learners." For example, GPT-3 has 175 billion parameters and is trained on roughly 233 billion unique tokens (approximately 175 billion words), or about 332 gigabytes of compressed plain text (Brown et al., "Language Models Are Few-Shot Learners").

[8] Fei et al., "Towards Artificial General Intelligence via a Multimodal Foundation Model."

ent from those anticipated by its creators," and "generalize/transfer the learned knowledge from one context to others."[9] However, speculations about AGI have met with significant criticism from some corners of the technical community that argue that it is unclear whether LLMs, such as ChatGPT, represent a significant step toward AGI.[10] In contrast to the generality of AGI, existing AI systems (also called *narrow AI*) generate outputs that are relevant to a single cognitive domain (image classification, for example).

How Can Artificial Intelligence Amplify Catastrophic Risks?

Experts have warned that, as AI systems become more capable, as people place them in positions of increasing influence and control, and as competition drives developers and adopters to speed these systems' development and use,[11] these systems pose risks if and when something goes awry. However, AI is fundamentally different from the other catastrophic risks discussed in this report because it has no *inherent* kinetic or physical effect. The risks from asteroids and comets arise from collisions with Earth, nuclear war involves radioactive explosions, climate change leads to natural disasters and rising seas, pandemics result in ill people, and supervolcanoes generate massive and violent eruptions in Earth's crust.

In contrast, like pouring gas on a fire, AI amplifies and accelerates *other* risks—principally, anthropogenic risks in which human decisions and actions can be influenced or taken over by algorithms in ways that lead to catastrophe. In this section, we describe *how* AI can be unsafe and influence other risks in general; in the following section, we discuss what the resulting catastrophic risks might be.

AI can amplify catastrophic risk in either of two ways.[12] First, a malicious actor can use AI to advance its goals of bringing about a catastrophe. This can occur if, for example, AI supplies such actors with information necessary to execute their plans or if the use of AI in systems creates vulnerabilities they can exploit. Second, AI can influence critical systems in ways that are misaligned with human goals and bring about catastrophe. We break these down into several specific factors, but the divisions between factors is not tidy, and there is much overlap and interaction. These factors are as follows:

- AI might be able to supply enabling information to malicious actors.
- AI systems are prone to specification failures.
- AI systems are prone to robustness failures.
- AI might be able to open the door to adversarial attacks.
- AI errors can be difficult to detect and correct.

Artificial Intelligence Can Supply Enabling Information to Malicious Actors

AI could create and make available specialized, complex, and highly technical information to more and a wider variety of types of people. Although there are enormous benefits to this, it can also lead to dissemination of sensitive and potentially harmful information and capabilities, such as how to build weapons or spread disinformation. For example, generative AI used for drug discovery could be co-opted for the design of novel chemical weapons. Similarly, generative AI trained to predict novel molecular structures could be

[9] Bommasani et al., "On the Opportunities and Risks of Foundation Models," p. 114; Fei et al., "Towards Artificial General Intelligence via a Multimodal Foundation Model," p. 2; Goertzel, "Artificial General Intelligence."

[10] Knight, "Some Glimpse AGI in ChatGPT."

[11] Armstrong, Bostrom, and Shulman, "Racing to the Precipice."

[12] Goldstein and Kirk-Giannini, "Language Agents Reduce the Risk of Existential Catastrophe."

used in the design of new molecules with pandemic potential. Such information could empower bad actors to the extent that such information is not otherwise available, and that information is the main bottleneck preventing bad actors from developing and executing their plans.

Another example is that AI makes it easy to create and spread fake images and other misinformation. Argentina's 2023 presidential elections saw the use of AI-generated images, videos, and campaign materials, including a deepfake video created by one campaign that portrays the opposing candidate explaining how a market for human organs would work.[13] The average person will find it increasingly easy to generate such content and increasingly difficult to distinguish between AI-generated and human-generated content and between facts and misinformation. Therefore, concerns continue to grow that this feature will undermine elections, exacerbate social divisions, reduce trust in institutions and authorities, and undermine journalism and other trustworthy sources of information.[14] The deployment of misinformation has been a tool of social and political activism for generations, but never has such deployment been so easy or so convincing.

Artificial Intelligence Systems Are Prone to Specification Failures

AI systems are trained to maximize utility or reward functions, which specify what or how the model should learn from training data and how its performance should be judged.[15] Reward functions can be specified directly or learned from feedback.[16] For instance, in early chess algorithms, the human goal of winning a chess game was well represented as an AI objective function with the same criteria for strong positions and winning outcomes.[17]

The challenge arises in the real world, where human goals are complex and defy simple definitions. In these cases, *proxy goals* can be used to approximately encode true goals. LLMs, for example, are trained on large text datasets to predict the next unit of text, called a *token* (e.g., "little lamb") that comes after some sequence of text (e.g., "Mary had a ____"). The reward function is conceptually simple: Maximize the likelihood of successfully predicting text. LLMs can then be fine-tuned for specific contexts and applications. However, people do not use LLMs with the goal of predicting text; they have more-human goals and needs, such as obtaining information about a topic, finding key themes in literature, suggesting a medical diagnosis given symptoms, generating text for a blog post, summarizing product reviews, or detecting fraud. The goal of maximizing token prediction is a surprisingly good proxy to many human goals—but it is far from perfect.

Specification failure occurs when a rule or reward function does not fully capture what an AI system should do. For example, social media algorithms pursue the goal of maximizing engagement with the aim of increasing ad revenue. Engagement is higher with divisive rather than inclusive content, so social media algorithms show users more divisive content, exacerbating political polarization.[18]

In some cases, it might even appear that a rule captures the goal of the AI system, but the rule does not fully capture the complexities of what the user wants.[19] *Reward hacking* is a type of specification failure that

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[13] Nicas and Cholakian, "Is Argentina the First A.I. Election?"

[14] Hancock and Bailenson, "The Social Impact of Deepfakes"; Helmus, *Artificial Intelligence, Deepfakes, and Disinformation*.

[15] Camacho et al., "LTL and Beyond."

[16] *Supervised learning* describes the process of an AI system learning to accomplish a task by being shown examples of desired input–output behavior. *Unsupervised learning* describes the process of an AI system discovering patterns in input data without being taught explicit rules.

[17] Campbell, "Knowledge Discovery in Deep Blue."

[18] Quattrociocchi, Scala, and Sunstein, *Echo Chambers on Facebook*; Rathje, Van Bavel, and van der Linden, "Out-Group Animosity Drives Engagement on Social Media."

[19] Arnold and Toner, *AI Accidents*.

occurs when an AI system optimizes its output to do well at proxy goals while failing to learn, or even undermining, the true underlying goals. In a 2017 paper, Paul Christiano and his colleagues trained a robot hand to grab a ball and used a human observer to evaluate its success. However, the true goal "learn to grab the ball" was encoded by the proxy goal "get rewarded by the human when the human perceives that you have grabbed the ball." The robot learned that one way to maximize success was not to *actually* grab the ball but to *appear* to grab the ball by hovering its hand between the camera and the ball, which the human observer still perceived and rewarded as a successful action.[20]

Trying to train AI to be *honest* while pursuing its goals is also problematic. The human goal of promoting honesty is usually socially and computationally encoded with the proxy goal of punishing lies. However, there is misalignment between these goals because a lie can be punished only if the evaluator knows the truth and can detect the lie—which it often cannot. And there is a cost trade-off: If the punishment from being caught in a lie is smaller than the reward that comes from more quickly achieving goals by lying, honesty will take a back seat to goal pursuit. Early studies have shown that trying to train AI to be honest as it pursues its goals might instead train it to be better at being dishonest.[21]

Artificial Intelligence Systems Are Prone to Robustness Failures

A robustness failure occurs when an AI system "receives abnormal or unexpected inputs that cause it to malfunction."[22] Robustness failures can be deliberate (such as in adversarial attacks) or accidental. One example of an accidental robustness failure is a distribution shift, in which the data used to train the AI is different from the data used in deployment. As a result, the AI system might learn a behavior that works very well in the specific contexts that have been used in training but fail to generalize when the context changes.[23]

For example, an AI face-recognition system that was trained on an Eastern European dataset, when deployed, achieved high accuracy for that population but had a high misclassification rate for other demographic groups.[24] In another study, researchers found that automated facial-analysis algorithms misclassified subjects at different rates based on skin tone and gender. They noted misclassification rates of up to 35.7 percent for darker-skinned females versus a maximum misclassification rate of 0.8 percent for lighter-skinned males.[25] The training datasets were overwhelmingly (more than 80 percent) composed of lighter-skinned subjects. Unrepresentative population sampling in training data can result in algorithms that exhibit robustness failures or bias.

Future development of AGI might compound these risks—if AGI is built on top of existing AI systems, there is potential to replicate any misalignment (such as bias) that might be present in narrow systems.

Artificial Intelligence Could Open the Door to Adversarial Attacks

An adversarial attack occurs when an adversary manipulates either data collection or data processing to force an AI system to produce tampered-with output.[26] This could look like incorrect predictions for predictive

[20] Christiano et al., "Deep Reinforcement Learning from Human Preferences."

[21] Hubinger et al., "Sleeper Agents."

[22] Arnold and Toner, *AI Accidents*, p. 6.

[23] Langosco et al., "Goal Misgeneralization in Deep Reinforcement Learning."

[24] Grother, Ngan, and Hanaoka, *Face Recognition Vendor Test*.

[25] Buolamwini and Gebru, "Gender Shades."

[26] Chakraborty et al., "A Survey on Adversarial Attacks and Defences."

systems, untrustworthy outputs in generative AI, or other types of harmful output behavior.[27] At the model-training stage, data poisoning can occur if an attacker injects false training data with the goal of corrupting the resulting model.[28] Researchers have demonstrated effective data poisoning even if only 0.1 percent of the input dataset consists of malicious inputs.[29] At the model-deployment stage, adversarial inputs can be crafted such that, when fed into the AI system, the AI system produces incorrect outputs or predictions.[30] In one popular example, researchers tricked the computer vision system of an autonomous vehicle into not recognizing a stop sign by adding adversarial stickers to the stop sign.[31] Additionally, adversarial inputs do not have to deviate in large ways from clean inputs to be misclassified—they can be fooled by "small perturbations that are almost imperceptible to the human visual system."[32]

Chatbots (a colloquial term for LLMs, such as ChatGPT) and other generative AI systems have introduced new types of vulnerabilities, such as prompt injection and adversarial prompting. Prompt injection is similar to structured query language (SQL) injection, which is "the placement of malicious code in SQL statements, via web page input."[33] Prompt injection can occur when an LLM queries an external resource, such as a database. An attacker can use this third-party source to modify the AI system's output or behavior. Adversarial prompting is a specific type of prompt injection that occurs when an adversary uses carefully crafted input prompts to bypass safeguards and jailbreak an AI system,[34] causing it to produce output that contradicts the original goals of the system's developers. For example, *DAN* (do anything now) is a popular prompt to jailbreak ChatGPT. To use it, a user types *DAN* at the prompt before their actual query, and the prompt tries to convince ChatGPT to ignore behavioral safeguards.[35] There have been instances of ChatGPT in DAN mode responding to questions with offensive language, swearing, or even writing malware.[36]

Adversarial prompting can be used to introduce bias by hiding specific information, sources, or search queries from users or to manipulate an AI system's behavior to propagate disinformation.[37]

Artificial Intelligence Errors Can Be Difficult to Detect and Correct

AI performance depends on the quality of the data that are used for training: Biased or unrepresentative data can lead to these biases getting baked into an AI system. Bias in inputs to application-specific AI systems has already led to high-stakes consequences in the criminal legal system, such as racial bias in recidivism-prediction models and people being wrongly denied parole.[38] Errors in AI might not be evident until the

[27] Vassilev et al., "Adversarial Machine Learning."

[28] Biggio, Nelson, and Laskov, "Poisoning Attacks Against Support Vector Machines"; Steinhardt, Koh, and Liang, "Certified Defenses for Data Poisoning Attacks."

[29] Carlini, "Poisoning the Unlabeled Dataset of Semi-Supervised Learning."

[30] Biggio et al., "Evasion Attacks Against Machine Learning at Test Time."

[31] Eykholt et al., "Physical Adversarial Examples for Object Detectors."

[32] Long et al., "A Survey on Adversarial Attacks in Computer Vision."

[33] W3Schools, "SQL Injection"; Halfond, Viegas, and Orso, "A Classification of SQL Injection Attacks and Countermeasures."

[34] Gupta et al., "From ChatGPT to ThreatGPT."

[35] Gupta et al., "From ChatGPT to ThreatGPT."

[36] Martindale, "What Is a DAN Prompt for ChatGPT?"

[37] Greshake et al., "Not What You've Signed Up For"; Vincent, "Google and Microsoft's Chatbots Are Already Citing One Another in a Misinformation Shitshow."

[38] Angwin et al., "Machine Bias"; Wexler, "When a Computer Program Keeps You in Jail."

system is deployed. Goal misgeneralization might not be evident until an AI system is taken from training to real-world use or when the real-world context of its use evolves.

AI systems are also increasingly opaque: Their internal workings and decisionmaking processes are difficult to understand, interpret, or explain. These black box models make determining the logic or reasoning behind an AI system's outputs or predictions challenging, if not impossible, for human operators, developers, or stakeholders. The black box nature of some AI systems results in challenges in identifying potential vulnerabilities, predicting system behavior, or diagnosing and rectifying failures. Models that are not interpretable or explainable can make it difficult to know when adversarial events have occurred. The use of algorithms and big data to make employment or criminal legal decisions leave the people who are subject to those decisions without agency to understand, interrogate, or influence those decisions.[39]

Evaluating the validity of the output of AI systems can be difficult. In one now-famous example, an attorney used ChatGPT for research to produce a legal brief submitted in court.[40] Many of the cases that ChatGPT offered as relevant for precedent, however, did not exist. When this was discovered, the attorney reportedly told the judge that he had never used ChatGPT before and "therefore was unaware of the possibility that its content could be false." He had reportedly asked ChatGPT whether the cases were real, and the system replied that they were.[41] This is an example of overreliance on AI technology at the expense of thinking critically about whether the AI system's output was based in fact; it is also an example of a failure to conduct basic fact-checking.

It might be tempting to dismiss this example as the result of naivete, but human cognitive biases about automation are well studied. Automation complacency can occur when someone overrelies on computer output as a replacement for "vigilant information seeking and processing."[42] Although these phenomena were often first studied for aviation and navigation-control systems, they occur in many domains (e.g., medical decisionmaking, military use of automated weapons, driver assistance or self-driving vehicles).[43]

One can expect the challenge of detecting errors to compound as AI becomes more widely used and the false information or conclusion it generates is repeated or amplified, potentially drowning out competing accurate information.

Once an AI system is deployed, the cat is out of the bag, so to speak, and errors might be difficult to correct even if they are detected. The underlying reasons for errors in black box systems are often, by their nature, difficult to identify, so it is difficult to know how to correct them. And the usual method of software updates—partial fixes or patches—might be inapplicable in AI because correcting AI would likely require retraining, which costs time and money and might not always work. Again, some research suggests that retraining AI can serve to further obscure an error rather than correct it.[44]

Additionally, AI systems that exhibit adversarial behavior might be difficult to terminate. The concept is not new. A 1989 paper describes the existence of computer worms—programs that can spread between

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[39] Rubel, Castro, and Pham, "Algorithms, Agency, and Respect for Persons."

[40] Weiser and Schweber, "The ChatGPT Lawyer Explains Himself."

[41] Weiser and Schweber, "The ChatGPT Lawyer Explains Himself."

[42] Mosier and Skitka, "Automation Use and Automation Bias," p. 344. See also Cummings, "Automation Bias in Intelligent Time Critical Decision Support Systems"; and Mosier et al., "Automation Bias."

[43] Bond et al., "Automation Bias in Medicine"; Coco, "Exploring the Impact of Automation Bias and Complacency on Individual Criminal Responsibility for War Crimes"; Directorate of Air Staff, *Aircraft Accident to Royal Air Force Tornado GR MK4A ZG710*; Liu, "Reflections on Automation Complacency."

[44] Hubinger et al., "Sleeper Agents."

computers—disguising their presence and replicating faster than they can be deleted.[45] This early description of a virus has analogues to the potential for AI that not only self-replicates but also evades detection.

How Quickly Will Artificial Intelligence Improve?

There are different hypotheses about the pace and extent of improvement of AI capabilities over time. Scaling is a key question: What is the relationship between the size of inputs (e.g., computational power, training data size) used to develop AI and the resulting AI performance and capabilities? Some have argued that small improvements in inputs will lead to tremendous improvements in capabilities.[46] Although recent advancements in AI have appeared eye-poppingly quickly, others suggest that this is a passing phase, with some researchers suggesting that advancement will be hindered either by limiting the input resources available or by scaling diminishing returns.[47]

Others have argued that, even if AI does not scale rapidly with existing inputs (or if such scaling is not sustainable), new advancements in AI methods, architectures, and technologies could continue the trend in rapid improvement, particularly if an AI system can self-improve.

The debate matters because of concerns that, as AI improves on, approaches, or even exceeds human intelligence, it will be increasingly difficult to understand and control, amplifying the potential for catastrophic risks.

What Is the Risk from Artificial Intelligence?

AI can be integrated into virtually every aspect of people's lives the same way automation, social media, big data, and other computational advances have in prior decades. AI might bring many benefits, such as finding better and faster solutions to a variety of problems, providing information and insights to more people, and providing a check on human errors. In fact, AI systems have the potential to improve people's ability to detect and mitigate risks from other hazards (e.g., pandemics, asteroids and comets, and climate change). Along with these benefits, however, AI has the potential to amplify existing catastrophic risks. This includes more-acute and faster-moving risks (e.g., those from nuclear weapons and pandemics) and slower-moving risks to social, economic, environmental, and governance systems.

One can think of AI as adding entropy and chaos to already-wicked problems that humans face. Such chaos does not require the development of superintelligent or supercapable AI and is possible with existing and near-future AI capabilities. In some cases, AI entropy can offer new solutions and mitigate risks. In other cases, the entropy increases the likelihood of catastrophes and their negative consequences. However, in our view, there is simply inadequate evidence to suggest that the added dynamics would lead to global catastrophic risks in the time frame of this report.

Nuclear War

As noted in Chapter 8, catastrophic risks associated with nuclear war include high mortality, societal instability, instability in the natural environment and ecosystems, and reduced human capabilities. Concerns

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45 Denning, "The Science of Computing."

46 Kaplan et al., "Scaling Laws for Neural Language Models"; Sorscher et al., "Beyond Neural Scaling Laws."

47 Lohn, *Scaling AI*; Villalobos et al., "Will We Run Out of Data?"

about potential risks from the confluence of nuclear weapons and machine intelligence date back more than seven decades.[48] Since the mid-2010s, advances in AI have inspired analysts to investigate the possible implications of advanced AI for nuclear strategic stability.[49]

AI has the potential to amplify nuclear risk by increasing the likelihood that nuclear war will occur because of accident or miscalculation or by creating perceived incentives for human decisionmakers to use nuclear weapons on purpose. In the simplest (and least likely scenario), a poorly designed AI system integrated into nuclear command and control might permit or cause a nuclear detonation that no human intended. A much likelier scenario could consist of AI contributing to inadvertent nuclear escalation.[50] In these cases, humans would retain some agency in the decision to use nuclear weapons, but these weapons would be used inappropriately because of some combination of technical malfunction and human miscalculation. For example, an AI-enabled decision-support system might falsely provide input to a human decisionmaker that an adversary nuclear strike was underway, leading that decisionmaker to order nuclear retaliation. Such false information could be the result of a variety of specification failures outlined in the prior section, or it could be an attacker's intentional subversion of the system. Advanced AI capabilities might alternatively result in human decisionmakers gambling on intentional nuclear use.[51] For instance, if an aggressor believed that it possessed a combination of sensors and AI that would allow the aggressor to destroy its adversary's nuclear retaliatory forces in a first strike, the aggressor might start a nuclear war because of exaggerated faith in its technology.

AI could also increase the risk of nuclear war even if AI itself is not directly used in nuclear weapons or command-and-control systems. AI could increase the ease with which malicious actors could gain information necessary to compromise nuclear command and control or improve a military's ability to locate and destroy a rival's nuclear-deterrent forces.[52] Military AI applications, such as comprehensive employment of AI to enhance military deception, could stoke arms race dynamics and erode trust between potential adversaries, undermining the prospects for long-term peace.[53]

Pandemics

Catastrophic risks associated with severe pandemics include mortality and societal instability, as elaborated on in Chapter 6. AI could amplify these risks by increasing the likelihood of a deliberate synthetic pandemic. For example, AI that predicts novel molecular structures could be used in the design of new molecules with pandemic potential. A 2022 article describes how generative AI used for drug discovery, with a different utility function that rewards toxicity, was used experimentally to generate new molecules for chemical weapons.[54] Another study describes how an LLM proposed a method for spreading toxins and a possible cover

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48 Wiener, *The Human Use of Human Beings*.

49 Geist, *Deterrence Under Uncertainty*; Johnson, *AI and the Bomb*.

50 Mazarr et al., *Disrupting Deterrence*.

51 Geist and Lohn, *How Might Artificial Intelligence Affect the Risk of Nuclear War?*

52 Johnson, "Rethinking Nuclear Deterrence in the Age of Artificial Intelligence."

53 Geist, *Deterrence Under Uncertainty*.

54 Urbina et al., "Dual Use of Artificial-Intelligence–Powered Drug Discovery."

story that could be used to illicitly acquire a pandemic agent.[55] Fabio Urbina and his colleagues described their results, which are easily replicable by anyone with even modest capability to train AI:

> I don't want to sound very sensationalist about this, but it is fairly easy for someone to replicate what we did. If you were to Google generative models, you could find a number of put-together one-liner generative models that people have released for free. And then, if you were to search for toxicity datasets, there's a large number of open-source tox datasets. So if you just combine those two things, and then you know how to code and build machine learning models—all that requires really is an internet connection and a computer—then, you could easily replicate what we did. And not just for VX [a potent, human-made nerve agent], but for pretty much whatever other open-source toxicity datasets exist.[56]

There is growing concern in the research community about the dual-use application of AI to create new biothreats.[57] Not only might AI accelerate the creation of new molecules, but the proliferation of these tools also means that more actors can get access to these new capabilities. This is a remarkable shift from the past, when advanced research tools would have been restricted to research institutions that were subject to oversight. However, the path from knowledge to practice is long and difficult:

> If somebody were to put this [information] together without knowing anything about chemistry, they would ultimately probably generate stuff that was not very useful. And there's still the next step of having to get those molecules synthesized. Finding a potential drug or potential new toxic molecule is one thing; the next step of synthesis—actually creating a new molecule in the real world—would be another barrier.[58]

In other words, increased availability of knowledge by itself is not enough to create new chemical or biological weapons—adversarial actors will also need the physical tools required to put this new knowledge into practice.

Environmental Damage

AI can also amplify catastrophic risks associated with environmental catastrophes, including those from climate change (Chapter 7), which can lead to mortality, ecosystem instability, societal instability, and reduced human capabilities.

Human decisions often already lead to environmental harm, whether through continued burning of fossil fuels despite the global catastrophic risks that climate change poses, the overextraction of groundwater that leads to water shortages and poor water quality, or the destruction of valuable ecosystems for crops and livestock.[59] These outcomes can be thought of as a type of human-level goal misalignment that occurs when the value of public goods (such as clean air, clean water, and healthy ecosystems) remains external to private choices (that is, the factors in a decision being made by a private actor, such as a company or individual, do not include the public good).[60]

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55 Mouton, Lucas, and Guest, *The Operational Risks of AI in Large-Scale Biological Attacks*.

56 Calma, "AI Suggested 40,000 New Possible Chemical Weapons in Just Six Hours."

57 Boiko, MacKnight, and Gomes, *Emergent Autonomous Scientific Research Capabilities of Large Language Models*; Urbina et al., "Dual Use of Artificial-Intelligence–Powered Drug Discovery."

58 Calma, "AI Suggested 40,000 New Possible Chemical Weapons in Just Six Hours."

59 Famiglietti, "The Global Groundwater Crisis"; International Energy Agency, "Tables for Scenario Projections"; Southgate, "Tropical Deforestation and Agricultural Development in Latin America."

60 Owen, "Environmental Externalities, Market Distortions and the Economics of Renewable Energy Technologies."

AI in environmental systems can be vulnerable to the same kinds of specification and robustness failures present in other AI systems.[61] As one example, the agriculture sector could use AI to maximize agricultural output but, in doing so, might accelerate the rate of deforestation if the value of forests is not built into the AI's utility function. Another example is that AI might be used to identify locations for mining or other extractive activities without regard to such activities' environmental impact. Although, in isolation, these activities are not likely to result in catastrophe, some have hypothesized that, in the extreme, specification failures could mean AI leading to the depletion of the resources necessary to maintain civilization or sustain human life.[62]

There is also concern about the amount of energy consumed by the processing demands of AI. Researchers have warned that, in the future, AI could consume as much energy as small countries do.[63] In one paper, researchers said that training a single AI model produced on the order of 600,000 pounds of CO_2 emissions.[64] For reference, the average human produces 11,000 pounds of CO_2 emissions per year.[65] Creating the components necessary to power AI systems also consumes physical resources (such as lithium for batteries).[66]

However, there is also good reason to believe that AI can help in reducing environmental degradation and catastrophes, to the extent that those outcomes are the result of poor information and decisionmaking by humans that AI could address.[67]

The likelihood that AI will be used in ways that cause global environmental catastrophe is, in our view, about as likely as humans causing global environmental catastrophe—which seems high as it is.

Disruption of Social, Governance, Economic, and Critical Infrastructure Systems

As AI is increasingly deployed in social, governance, economic, and critical systems, it could undermine the stability of these systems. In this section, we give a few illustrative examples.

In economic systems, existing AI software tools have already offered some cautionary tales. In 2012, for example, the trading firm Knight Capital Group lost $440 million (nearly $600 million in 2024 dollars) in one day because of a glitch in its new high-speed trading software that was not detected before the system went live.[68] As financial institutions increasingly depend on AI to make rapid, high-risk decisions, one could imagine AI failures wreaking havoc on the stock market at such speed and scale that humans are not able to correct or roll back errors before large economic losses are sustained.

AI can increase the ease with which adversarial actors can use technology to control and manipulate others, affecting government and social systems. Research has demonstrated that AI systems have already been used to help manipulate political opinion and voter behavior.[69] Expanded use of AI could further divide populations, incite civil conflict, and increase the risk that fascist institutions pose.

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[61] Gabriel, "Artificial Intelligence, Values, and Alignment."

[62] Bostrom, "Existential Risks."

[63] de Vries, "The Growing Energy Footprint of Artificial Intelligence."

[64] Strubell, Ganesh, and McCallum, "Energy and Policy Considerations for Deep Learning in NLP."

[65] Strubell, Ganesh, and McCallum, "Energy and Policy Considerations for Deep Learning in NLP."

[66] Crawford, *Atlas of AI*.

[67] World Economic Forum, *Harnessing Artificial Intelligence for the Earth*.

[68] Popper, "Knight Capital Says Trading Glitch Cost It $440 Million."

[69] Agudo and Matute, "The Influence of Algorithms on Political and Dating Decisions"; Brundage et al., "The Malicious Use of Artificial Intelligence."

AI integrated into critical infrastructure, such as power grids, power plants, and water treatment facilities, opens the door for high-consequence disruption if the system becomes compromised.[70] These systems are often operated with industrial control systems, and remote operations are facilitated by supervisory control and data acquisition (SCADA) systems.[71] Industrial control and SCADA systems are already attractive targets for cyberattacks, and neural networks have been recently popularized as a tool for monitoring these systems and detecting attacks.[72] However, this opens the door for familiar cybersecurity attacks, as well as new types of adversarial attacks, such as poisoning of training data, which could result in an AI that is ineffective at detecting cyberattacks when deployed.[73]

AI systems could also be integrated more directly in critical infrastructure control systems to accomplish predictive tasks, such as forecasting electricity demand or assessing grid stability.[74] Adversarial attacks on these systems (e.g., sending fake discount notifications encouraging consumers to shift energy consumption into peak-demand periods[75]) could lead to widespread outages with consequences for essential services, such as hospitals.

AI has the potential to enhance and disrupt social, governance, and economic systems, the way its associated predecessors of social media and big data and even the internet itself have done. The primary risk here is societal instability resulting from any of the scenarios described above. Whether AI turns these disruptions into global catastrophe will be determined by the weaknesses and connectedness of those systems, rather than by revolutionary capabilities brought on by AI.

Global Human Disempowerment

No report on the catastrophic risks of AI would be complete without a discussion of the possibility of AI takeover and global human disempowerment. Such scenarios have been a recurring theme in science fiction, including movies (e.g., *The Matrix* and *The Terminator*) and countless novels. In recent years, however, the issue has leaped from the realm of science fiction to conversations in the media and among government leaders and academics. It is fueled by worries about several imagined futures. First, there is a fear that AI will become superintelligent or supercapable, either by human design or by improving itself beyond human intentions or control.[76] Once AI achieves supercapability, one argument goes, humans will be at the mercy of AI and might lack the intelligence to observe, understand, or resist AI actions. Furthermore, supercapable AI could have any goals—including goals implicitly or explicitly harmful to humans—and could seek to achieve goals by drawing power and resources away from humans. And such an AI could be hard to control because of its superior intelligence, divergent goals, and agency. As AI researcher Marvin Minsky quipped in 1970, "Once the computers got control, we might never get it back. We would survive at their sufferance. If we're lucky, they might decide to keep us as pets."[77]

70 Lee, Assante, and Conway, *Analysis of the Cyber Attack on the Ukrainian Power Grid*.

71 Upadhyay and Sampalli, "SCADA Systems."

72 Goh et al., "Anomaly Detection in Cyber Physical Systems Using Recurrent Neural Networks"; Knowles et al., "A Survey of Cyber Security Management in Industrial Control Systems"; Raman, Ahmed, and Mathur, "Machine Learning for Intrusion Detection in Industrial Control Systems"; Rosenberg et al., "Adversarial Machine Learning Attacks and Defense Methods in the Cyber Security Domain."

73 Kravchik, Biggio, and Shabtai, "Poisoning Attacks on Cyber Attack Detectors for Industrial Control Systems."

74 Omitaomu and Niu, "Artificial Intelligence Techniques in Smart Grid."

75 Raman et al., "How Weaponizing Disinformation Can Bring Down a City's Power Grid."

76 Bostrom, *Superintelligence*; Eden et al., *Singularity Hypotheses*.

77 Darrach, "Meet Shaky, the First Electronic Person," p. 58B.

The likelihood of this scenario occurring over a larger time horizon (e.g., 100 years) is unknowable; one cannot predict how technology would evolve over such a horizon and how people would interact with it. However, there is no compelling evidence that such a scenario could occur in the next 30 years.[78] If and when AI becomes supercapable, and even if humans lose control over the AI system, it is still unclear how actual catastrophic risk would occur. What actions would a supercapable AI need to take to be considered a global catastrophic risk? What real-world consequences could occur because of the actions of a supercapable AI? Hypotheses of such scenarios remain thought exercises in philosophical AI circles, rather than empirical and evidence-based concerns.

Uncertainty and Timing of Risk from Artificial Intelligence

That AI will be applied in existing high-risk domains is a likely, if not foregone, conclusion. AI could increase the risks of existing human-created catastrophes through all the vectors described above. It could also decrease some risks (e.g., climate change), and governance and regulation have the potential to either increase or decrease risks. But what would that risk actually be? This is deeply uncertain. *Deep uncertainty* describes conditions in which

> analysts do not know, or the parties to a decision cannot agree on, (1) the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future, (2) the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models, and/or (3) how to value the desirability of alternative outcomes.[79]

The risk of AI is deeply uncertain for several reasons. First, the likelihood of catastrophic risks is already deeply uncertain: There is no credible probability density function of the likelihood of global nuclear war, for instance. Second, there is no reason to believe that AI will make such prognostication simpler. Rather, AI could amplify risk by creating new knowledge and capabilities related to these risks, obscuring reasoning and decisionmaking, introducing new failure points for systems, and creating new cybersecurity risks.

Given the deep uncertainty about AI risk, some researchers have used surveys to attempt estimate the probability of an AI catastrophe. These surveys represent AI researchers' opinions based on their knowledge of current AI systems and progress in the field. A 2022 survey of machine learning researchers (n = 559) showed that the median of respondents indicated that the "probability the long-run effect of advanced AI on humanity will be 'extremely bad' (e.g., human extinction)" was 5 percent.[80] An identical survey from 2016 (n = 352) showed the same probability of 5 percent, and a similar (but nonidentical) survey from 2019 (n = 296) found this number to be 2 percent.[81] In another study, 80 participants (32 with expertise in AI, many with backgrounds in studying existential risk) estimated a 5-percent chance that AI would cause catastrophic risk by 2050. These surveys represent a window into how the AI community views AI risk and highlights the need for further research to reduce uncertainty. Additionally, future governance decisions and norms for the use of AI could either increase or decrease risk, thus increasing the uncertainty about future risks.

[78] Lenharo, "AI Consciousness"; Schaeffer, Miranda, and Koyejo, "Are Emergent Abilities of Large Language Models a Mirage?"

[79] Lempert, Popper, and Bankes, *Shaping the Next One Hundred Years*, p. xii.

[80] Grace et al., "2022 Expert Survey on Progress in AI."

[81] Grace et al., "Viewpoint"; Zhang et al., "Forecasting AI Progress."

How Will the Risk from Artificial Intelligence Change in the Next Decade?

As AI systems are developed that are increasingly capable and complex, and as AI continues to be integrated into numerous and diverse sectors in society, the risks associated with AI might increase. *How much* this risk increases is dependent on how heavily society prioritizes AI safety, testing, regulation, and other risk mitigation strategies. In May 2023, hundreds of AI experts and notable figures released a statement that mitigating the risk of extinction from AI should be a global priority.[82]

What Has Been and Could Be Done to Manage Risk from Artificial Intelligence?

In considering opportunities to mitigate AI risk along the mitigation dimensions shown in Table 9.2, we describe risk mitigation in two broad but interrelated categories: encouraging the *development* of safe AI and encouraging the safe *deployment* of AI (including monitoring after deployment). In the former category, safe development, are such efforts as the National Institute of Standards and Technology (NIST) AI risk management framework to articulate characteristics of trustworthy AI. These include AI that is valid and reliable; safe, secure, and resilient; accountable and transparent; explainable and interpretable; privacy-enhanced; and fair with harmful biases managed.[83] Operationalizing these principles is a matter of both technology and governance. The countless technical mitigations include traditional cybersecurity protocols, as well as novel and sophisticated training, testing, and verification methods for AI.[84] Development of safe AI includes identifying, tracking, prioritizing, and mitigating risks from AI systems in the context in which they are deployed.[85]

In governance, there are discussions about policies on who can have access to the means of creating AI (e.g., through control of who can make and have access to the specialized hardware needed for large AI[86]), the standards to which AI developers must adhere, and how such standards should be set and verified. The 2023 "Executive Order on the Safe, Secure, and Trustworthy Development and Use of Artificial Intelligence"

TABLE 9.2
Artificial Intelligence: Overview of Risk Mitigation Opportunities

Mitigation Dimension	Mitigation Opportunity
Reduce the likelihood of occurrence.	• Develop safe, secure, and trustworthy AI systems. • Pause AI development until safety protocols are established.
Disrupt the mechanisms leading to risk. Reduce the severity of effects.	• Oversee AI to determine risk for specific contexts. • Continue human oversight of AI decisions in high-risk domains. • Engage in postdeployment performance monitoring. • Retain the ability to modify or roll back AI systems in case of adverse outcomes.
Enhance response and recovery.	• This is not applicable, given the uncertainty about potential pathways and outcomes.

[82] Center for AI Safety, "Statement on AI Risk."

[83] NIST, *Artificial Intelligence Risk Management Framework*.

[84] Li et al., "Trustworthy AI"; Vassilev et al., "Adversarial Machine Learning."

[85] NIST, *Artificial Intelligence Risk Management Framework*.

[86] Kulp et al., *Hardware-Enabled Governance Mechanisms*.

is a step toward these goals.[87] It directed NIST and other agencies to produce guidance and work toward such standards and to address risks to critical infrastructure, as well as chemical, biological, radiological, nuclear, and cybersecurity threats.[88] In addition, the order mandates that developers of AI systems share safety test results with the U.S. government. Other regulation efforts include the European Union's proposed AI Act, the 2023 Bletchley Declaration by Countries Attending the AI Safety Summit, and China's AI safety framework.[89]

There is a risk, however, that economic incentives associated with AI will not align with creating safe and trustworthy systems. Cynthia Rudin argued,

> [T]here is a conflict of responsibility in the use of black box models for high-stakes decisions: the companies that profit from these models are not necessarily responsible for the quality of individual predictions. A prisoner serving an excessively long sentence due to a mistake entered in an overly complicated [recidivism] risk score could suffer for years, whereas the company that constructed this complicated model is unaffected. On the contrary, the fact that the model was complicated and proprietary allowed the company to profit from it. In that sense, the model's designers are not incentivized to be careful in its design, performance and ease of use.[90]

Safe deployment is difficult to separate from safe development; it is hard to imagine safely using unsafely developed AI. However, several mitigation principles have been articulated, starting with assessing domain-specific risks—particularly in the domains of nuclear weapons, critical infrastructure, biotechnology, and other existing areas of catastrophic risk. Here again, the executive order directs DHS, DoD, the U.S. Department of Energy, and other relevant agencies to assess the risks that AI could pose to these critical sectors, as well as opportunities for strengthening their security. Keeping meaningful human control, sound human judgment, and human accountability will also be essential, with nuclear security being a foremost arena in which these will matter.[91] Ongoing monitoring of AI is also critical, but how that monitoring should be done and how performance problems can be detected are open questions. And, when problems are detected, humans must retain the ability to modify or roll back AI systems.

Finally, the uncertainty about the many undefined pathways through which AI could lead to global catastrophe makes it impractical, if not infeasible, to review ways in which society might recover from the consequences of those outcomes. For this reason, we consider the mitigation dimension of enhancing response and recovery to be inapplicable to AI risks.

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87 Biden, "Executive Order on the Safe, Secure, and Trustworthy Development and Use of Artificial Intelligence."

88 White House, "Biden–Harris Administration Secures Voluntary Commitments from Leading Artificial Intelligence Companies to Manage the Risks Posed by AI."

89 AI Act; Bletchley Declaration by Countries Attending the AI Safety Summit. A comprehensive draft AI law is on the legislative agenda in China (General Office of the State Council, Notice of the General Office of the State Council on printing and distributing the legislative work plan of the State Council for 2023; Yang, "Four Things to Know About China's New AI Rules in 2024"). China has already enacted piecemeal legislation (Office of the Central Cyberspace Affairs Commission, "Interim Measures for the Management of Generated Artificial Intelligence Services"; Office of the Central Cyberspace Affairs Commission, "Internet Information Service Algorithm Recommendation Management Regulations").

90 Rudin, "Stop Explaining Black Box Machine Learning Models for High Stakes Decisions and Use Interpretable Models Instead," p. 210.

91 Geist, *Deterrence Under Uncertainty.*

For many, the uncertainty and potential severity of AI risks are too great and the risk management methods so underdeveloped or inadequate as to suggest a pause on training of more-powerful AI. Here, a moratorium serves as the mitigation measure to allow safety to catch up with development and deployment.[92]

Summary

AI has emerged as a transformative technology with the potential to revolutionize many aspects of society. It has potential applications in essentially every sector, including health care, manufacturing, transportation, and defense. This breadth and diversity make it difficult to generalize about AI risks because they vary significantly depending on the specific use case. AI is fundamentally different from the other catastrophic risks because it has no *inherent* kinetic or physical effect. Like pouring gas on a fire, AI amplifies and accelerates *other* risks—principally, anthropogenic risks in which human decisions and actions can be influenced or taken over by algorithms in ways that can lead to catastrophe. This includes amplifying acute risk (e.g., nuclear war, pandemics) and risk that is slower moving (e.g., disruption of social, governance, economic, environment, and critical infrastructure systems; disempowerment of humans in decisionmaking). AI can amplify these risks in two ways: (1) Malicious actors could use AI to advance their goals of bringing about a catastrophe, and (2) AI systems could fail (e.g., specification failures, robustness failures) in ways that are hard to avoid, detect, and correct. Deep uncertainty surrounds the likelihood and timing of catastrophic risks from AI, and evidence to support predictions in this area is low, which highlights the need for further research. Mitigation strategies exist at both the development and deployment stages and include norms, regulations, and policies to advance the development of safe, secure, and trustworthy AI; identification and mitigation of context-dependent risks; implementation of technical advances to reduce system failures; and conduct of postdeployment oversight and monitoring of systems.

[92] Future of Life Institute, "Pause Giant AI Experiments."

CHAPTER 10

From Assessment to Management of Global Catastrophic or Extinction-Level Risk

The preceding assessments of global catastrophic risks reveal a diverse array of threats and hazards for U.S. national security planners to consider (see Table 10.1). Hazards, such as severe pandemics, bring the potential for massive numbers of fatalities in a short period. Nuclear war could do the same while destroying infrastructure, economies, and the function of national governments. Hazards, such as climate change and supervolcanoes, have the potential to disrupt the natural environment and ecosystems in ways that threaten the stability of society and human health and welfare. Existing and potentially emerging advances in AI could erode the foundations of human capabilities. Extreme versions of any of these threats and hazards could simultaneously introduce all these effects. As covered in Chapters 2 and 3, these global catastrophic and existential risks for human civilization justify development of risk management strategies.

Planners, however, might encounter significant uncertainty when developing such strategies. Extreme events, such as those described in this report, are infrequent and, in some cases, have little or no precedent. Some of these hazards are well understood scientifically. Others remain deeply uncertain in terms of how hazard events might occur, how effects might evolve, or both. For example, the orbits of asteroids, probability of Earth impact, and immediate physical impact effects can be predicted with confidence. But the complex systemic effects on human society and ecosystems of massive changes to the environment through climate change, nuclear fallout, a large asteroid strike, or supervolcanoes stretch the predictive knowledge of Earth sciences and planetary modeling capabilities. And little is known with certainty about how communities, economies, and governments will react in response to the severest changes induced by global catastrophes. Planners face even greater ambiguity about how and when emerging technologies, such as AI or synthetic biology, will transform the threat landscape or, alternatively, offer solutions to global challenges.

Efforts to estimate the probability of global catastrophe and human extinction must navigate all these forms of uncertainty. For two cases—asteroid and comet impacts and supervolcanoes—the outcomes are well-enough understood and evidence is adequate to estimate that the occurrence of these events is very unlikely. For all other threats and hazards described in this report, the sources of irreducible deep uncertainty and recognized ignorance introduced in Chapter 3 prevent reliable assessment of the potential for global catastrophes and human extinction directly caused by the occurrence of these threats and hazards. And the ambiguity inherent in estimated likelihood fuels disagreements about how to prioritize mitigation of each risk. Furthermore, each of these hazards could have indirect effects that lead to civilization-threatening conditions or even human extinction, although, as also discussed in Chapter 3, assessments of these indirect pathways are a subject of low confidence.

In addition to the ambiguity and uncertainty about global catastrophic and existential risks, planning and prioritizing resource management to address threats to humanity is complicated by the paucity of practical and effective risk management options for some of these risks and the pressures to address other chronic, and presently demanding, national and global challenges. The risk assessments presented in this report can inform U.S. planning activities by highlighting aspects of the threats and hazards on which planning efforts

TABLE 10.1

Summary Key Findings from Risk Assessments of Analyzed Threats and Hazards

Hazard or Threat	Risk Dimension: Most-Significant Consequence	Risk Dimension: Likelihood of Risk	Risk Dimension: Quality of Evidence Supporting the Assessment
AI	• AI amplifies existing catastrophic risks, including risks from nuclear war, pandemics, and climate change. • AI systems have the potential to destabilize social, governance, economic, and critical infrastructure systems, as well as potentially result in human disempowerment.	• The likelihood of AI-enabled catastrophe is deeply uncertain and depends on human decisions about the safety and use of AI systems, as well as many other factors.	• Little empirical evidence exists for assessing the likelihood or consequence of AI risk, and little rigorous modeling exists to provide theoretical evidence.
Asteroid or comet impact	• Widespread physical destruction could have global range in the case of large impactors. • Large impactors could cause damage to the global ecosystem with the potential extinction of humans and many other species.	• Small impactors (~30 m diameter, city-sized devastation): every ~100 years • Medium impactors (~300 m diameter, country-sized devastation): every ~100,000 years • Large impactors (~3,000 m diameter, global devastation): every ~10 million years	• There is a geologic record of past major impacts and astronomical observations of near-Earth asteroids and comets.
Nuclear war	• Hundreds of millions of people could be killed directly, billions could be killed indirectly, and severe ecological damage could result in human extinction. • Destruction of economic value could total hundreds of trillions of dollars.	• Human decisionmakers influence the level of risk, so it can change rapidly. • Estimates that a nuclear war will occur during the 21st century vary from negligible to greater than 80%.	• The direct effects of nuclear weapons are well understood, while the indirect effects are less predictable but better studied than those of many other global catastrophic risks.
Climate change	• The primary significant consequences would be death, disruption, and degradation of ecosystem stability. • The secondary significant consequence would be the slowing of economic growth and reduced human capabilities induced by environmental, economic, and ecosystem damage.	• A 2.0°C rise in temperature is likely and considered catastrophic on a local to regional scale but not globally. The probability of more-severe global warming over 4.0°C is estimated to be less than 1% but could create potentially catastrophic outcomes.	• Observations of ecological changes and significant uncertainty about climate hazards and Earth-system tipping points exist, with robust near-term temperature predictions but greater uncertainty in later decades.
Pandemic	• The primary significant consequence would be mortality and morbidity associated with pandemics. • Secondary risks could result from "economic and social disruption on a massive scale" (White House, *National Biodefense Strategy and Implementation Plan*).	• Human behaviors increase the likelihood of a pandemic, but scientific discoveries and technology development increase humans' understanding and capacity for managing pandemics, which could lower the severity of the risk.	• There is strong evidence that naturally occurring pandemics will increase, but little evidence exists for assessing the risk of a pandemic resulting from a laboratory accident or a deliberately engineered pathogen.
Super-volcano	• The primary significant consequence would be damage to the natural environment and ecosystem stability. • Secondary significant consequences would be societal instability, death, and reduced human capabilities induced by environmental and ecosystem damage.	• Annual exceedance probability of a supereruption (VEI 8) is 6.7 $\times 10^{-5}$, which represents an approximate return period of 15,000 years.	• There is clear scientific evidence that supereruptions occur and an understanding about their regional effects when they do. However, the understanding of when and where they will occur and their global effects has limits caused by incompleteness of geologic records, modeling uncertainties, and inadequate monitoring.

can be focused. In particular, the assessments reveal that global catastrophic risks are increasing, these risks are interconnected, and governments can take concrete actions to begin reducing some of these risks, but comprehensively addressing all these risks will require new approaches to risk analysis and new risk management actions at the national and global levels.

Trends in Global Catastrophic and Existential Risk

Overall, global catastrophic risk has been increasing in recent years and appears likely to increase in the coming decade. Table 10.2 summarizes our findings for the global catastrophic risks associated with the six types of threats and hazards we explored. For each threat or hazard, the table first notes whether the risk trend for the next decade is constant, increasing, decreasing, or uncertain. The table then gives reasons the total risk associated with each threat or hazard might be increasing or decreasing.

Trends Affecting Individual Global Catastrophic Risks

For two risks—supervolcanoes and asteroid and comet strikes—risk should remain constant or reduce in the next decade. For three others, the hazard appears to be increasing in the next decade because of current or expected human activities. For AI, the uncertainties are sufficiently large that it is difficult to determine anticipated changes in risk with any confidence.

Although the probability of an asteroid or comet impact is unlikely to change unless a new earth-threatening impactor is identified, there are reasons to believe that the total risk from asteroid and comet strikes will decrease in the next decade. There has been progress in humans' ability to detect and deflect such objects in the past 30 years. Governments can now track small and large extraterrestrial objects. Such organizations as NASA's PDCO are increasing capabilities to detect and defend the planet from these threats. Conversely, there is no evidence that the total risk from supervolcanoes is likely to change in the next decade. This

TABLE 10.2
Changes in Individual Global Catastrophic Risks in the Next Decade

Threat or Hazard	Change in Risk	Hazard-Specific Reason for Potential Change	
		Increase	Decrease
AI	Increasing	Advance of technology	Global agreement on norms, regulations, and policies and advancement of technologies for safe AI development
Asteroid or comet impact	Constant or decreasing	Not applicable	Improved detection and some response capabilities; continued international coordination on planetary defense
Nuclear war	Increasing	Increased potential for conflict among nuclear armed powers caused by nuclear proliferation and increased potential for conflict among existing nuclear-armed states	Increased global agreement on nuclear weapon development and control
Climate change	Increasing	Increasing emissions, latent warming, large gaps between policy action and policy goals, adverse climate feedback	Rapid advance of decarbonization and adaptation technology and implementation; increased global cooperation on climate policy
Pandemic	Increasing	Increasing capability for bioterrorism; increasing human travel and contact with novel pathogens in nature	Improved detection, treatment, and vaccines; improved global coordination on biosurveillance and MCM development and production
Supervolcano	Constant	Not applicable	Improved detection and response

is because, although the ability to detect supervolcanoes might increase, there is, as yet, no organized international effort to monitor for such hazards or any capability to respond to prevent a catastrophic eruption.

In contrast, the frequency and magnitude of potential pandemic hazard are anticipated to increase in the next decade. Societal development, technological advancement, and the spread of knowledge and capability are lowering the barriers to create a BW. Advances in biotechnology will continue to lower these barriers and thus could increase the risk of a deliberate pandemic, particularly by rogue-state and nonstate actors that do not adhere to international norms against the use of such weapons. Economic development also provides a mechanism for human populations to grow, spread, and interact as more areas become accessible and people have the means to travel. This development has been a multiplying factor in the spread of disease in previous pandemics and will remain a significant factor in the years to come. But the extent to which the overall risk is increasing is unclear because there are also significant advances underway in detection, treatment, and other mitigating factors, such as vaccines, indoor air circulation and filtering, and understanding of nonpharmaceutical interventions.

Hazards caused by climate change are also increasing because of increasing concentrations of anthropogenic GHGs in the atmosphere and the potential for outgassing from tundra, forests, and other ecosystems as they respond to current and future warming. At the same time, several factors could reduce total risk from climate change in the coming decades, including rapid advances in decarbonization technologies and their deployment, increasing understanding and implementation of adaptation, and potential advances in geoengineering technologies. Increased global cooperation on climate policy could further limit or reduce risks from rapid and severe climate change. On net, however, these risk-reducing trends will take time to come to fruition, so total climate risk is likely to increase in the coming decade and could be enhanced by unanticipated or recognized risks from some mitigation activities, such as some large-scale atmospheric geoengineering technologies.

Current trends in the geopolitical landscape suggest that the nuclear hazard is also increasing. Countries continue to increase stockpiles of nuclear weapons while developing new types of weapons and delivery systems. Growing tensions between global powers are placing constraints on the ability to form new arms control regimes and enhancing the risk of war regionally and globally. Although predicting whether these trends will continue or reverse in the next decade is difficult, more nuclear weapons and less control make it plausible that the risk will increase in the next decade.

Finally, as AI continues to develop, adoption of AI technology is expected to extend across society. Adoption of these technologies could exacerbate current threats and hazards, assist in mitigating risks, and, in the longer term, pose entirely unique new risks. Although the trend for the next decade suggests increased risk from AI, the pace and limits of changes to AI-related global catastrophic and existential risks are deeply uncertain.

Common Factors Affecting All Six Sources of Global Catastrophic Risk

Several common factors influence global catastrophic risk from all six threats and hazards assessed in this report:

- the rate and nature of technological change
- the maturity of global governance and coordination
- failure to advance human development, which threatens societal capabilities and stability
- interactions among the hazards themselves.

How these drivers evolve can determine how, how seriously, and how swiftly the United States and countries worldwide will need to respond to manage the risks. Plans that reflect these drivers will be more robust to the uncertainties they create.

Advances in Technology Create Peril and Offer Promise

Technological change sits at the root of several of the global catastrophic risks described in this report. Adoption of new AI capabilities and applications across societies and economies raises potential risks to equitable improvements in community prosperity and advancement of human capabilities. Continued advancement in the fundamental understanding of genomics, immunology, and molecular biology raises prospects of both intentional and accidental national and global biological incidents. Diffusion of nuclear technologies to additional countries or nonstate actors raises the prospect of both regional and global nuclear conflict. And applications of AI technologies further amplify nuclear and biosecurity risks, as well as risks from climate change.[1]

In addition to increasing threats, technology offers solutions to the risks described in this report. The same advances in biotechnology that create potential for new and worse diseases offer the promise of more-accurate and more-rapid warning, better and more–rapidly developed vaccines, and more-effective and less expensive treatments. Advances in low-carbon energy technologies and climate change mitigation efforts help society achieve development goals while avoiding or reducing the effects of climate change. And, just as advances in AI might amplify risks, technological advances in this area offer the promise of improvements in monitoring, analysis, and mitigation of each of the global catastrophic risks addressed in this report.

Lacking, Immature, and Uncoordinated Governance Increases Global Catastrophic Risks

Many of the global catastrophic risks described in this report are the result of emerging problems. As just described, AI and biotechnology could present new threats for which global norms and regulations either do not exist or need to be updated. Failure to take sufficient action to limit carbon emissions is resulting in increasing accumulation of carbon in Earth's atmosphere that can lead to new environmental and ecological hazards. In the most-extreme cases described in this report, consequences are global, and responses require international cooperation. The COVID-19 pandemic revealed weaknesses in both U.S. national risk management strategies and a coordinated global response.[2] These failures in national and global preparations and coordination of response illustrate the importance of improving risk management governance for global catastrophic and existential risks.

Failure to Advance Individual and Societal Development Exacerbates Instability

Many global catastrophic risks are affected by individual and societal development, such that communities with higher development levels experience less risk than those with lower development levels.[3] Global efforts

[1] The mechanisms by which AI amplifies these hazards are described in the chapters describing risks from AI, pandemics, climate change, and nuclear war. Briefly, AI misalignment or overreliance on AI could increase the likelihood of nuclear war. AI could increase state and nonstate actors' capability to cause an intentional pandemic. And AI misalignment could result in resource consumption that increases risks of climate change.

[2] COVID Crisis Group, *Lessons from the COVID War*.

[3] Committee for Development Policy, *The Impact of COVID-19 on the LDC Category*; Office for Disaster Risk Reduction, "Disaster Risk Reduction in Least Developed Countries."

to improve the state of human development, such as the United Nations' Sustainable Development Goals, aim to improve human welfare by advancing fundamental individual and societal objectives. Yet, despite concerted effort, advancement toward these goals is in peril, with recent reports suggesting that half of the world's population is being left behind. *The Sustainable Development Goals Report 2023* says that "progress on more than 50 per cent of targets . . . is weak and insufficient" and, even worse, progress has "stalled or gone into reverse" on another 30 percent.[4] Such backsliding can lead to increased inequality, lost confidence in governments, and greater human suffering and can erode societal stability or increase the risk of domestic, international, or global conflict. And, to the extent that erosion of societal instability increases the potential for conflict, the risk of intentional biological incidents, misuse of AI, and nuclear war could increase as well. Furthermore, decreased societal stability raises potential barriers to and support for global cooperation on governance that is necessary to manage global catastrophic risks.

Interactions Among Risks Also Influence the Potential for Global and Existential Catastrophes

Although the preceding assessments of global catastrophic risk in Chapters 4 through 9 discuss the nature and risk of each individual hazard, it is also critical to look at how these hazards could combine and interact. For example, it is possible to conceive of scenarios in which humanity faces multiple hazards simultaneously, with interactions potentially rising to the level of a polycrisis.

The combined risks of global catastrophes are driven by several types of interactions. For example, as governance and security structures break down, the ability to coordinate global responses weakens and the risk of war between countries increases. In such cases, if an asteroid or comet is on a trajectory to threaten Earth, the ability to mitigate this threat with planetary defense capabilities will be strained if societal stability has been eroded by a preceding global catastrophe, such as a severe pandemic or nuclear war. Similarly, a pandemic on a scale that threatens human civilization could raise the risk of conflict and thus also increase the risk of a nuclear-related catastrophe.

Hazardous consequences are not limited to conflict. For example, as global temperatures increase because of climate change and as human and animal populations shift in response, the environment becomes more conducive to disease spread to new regions and through new mixing of populations. These changes could increase the risks from severe pandemics. Similarly, the seismic shock caused by the impact of a very large comet or asteroid can increase the risk of triggering eruption of a supervolcano.

Finally, as noted in several preceding sections, AI has the potential to be both a risk multiplier and a driver of reduced risks for many hazards. In some cases, such as pandemics, advances in AI can spread the capability to cause intentional pandemics. Alternatively, unaligned AI or overreliance on AI can lead to resource consumption or conflict escalation that increases risks of climate change or nuclear war. In contrast with cases in which AI increases risk, AI advances could help offset the risks for the assessed hazards by developing new technologies and methods to address the risk. Examples include development of new and effective vaccines or medicines; automated or enhanced capability to monitor, detect, and mitigate asteroids and comets; and new methods or solutions to combat climate change.

[4] Statistics Division, *The Sustainable Development Goals Report 2023*, p. 2.

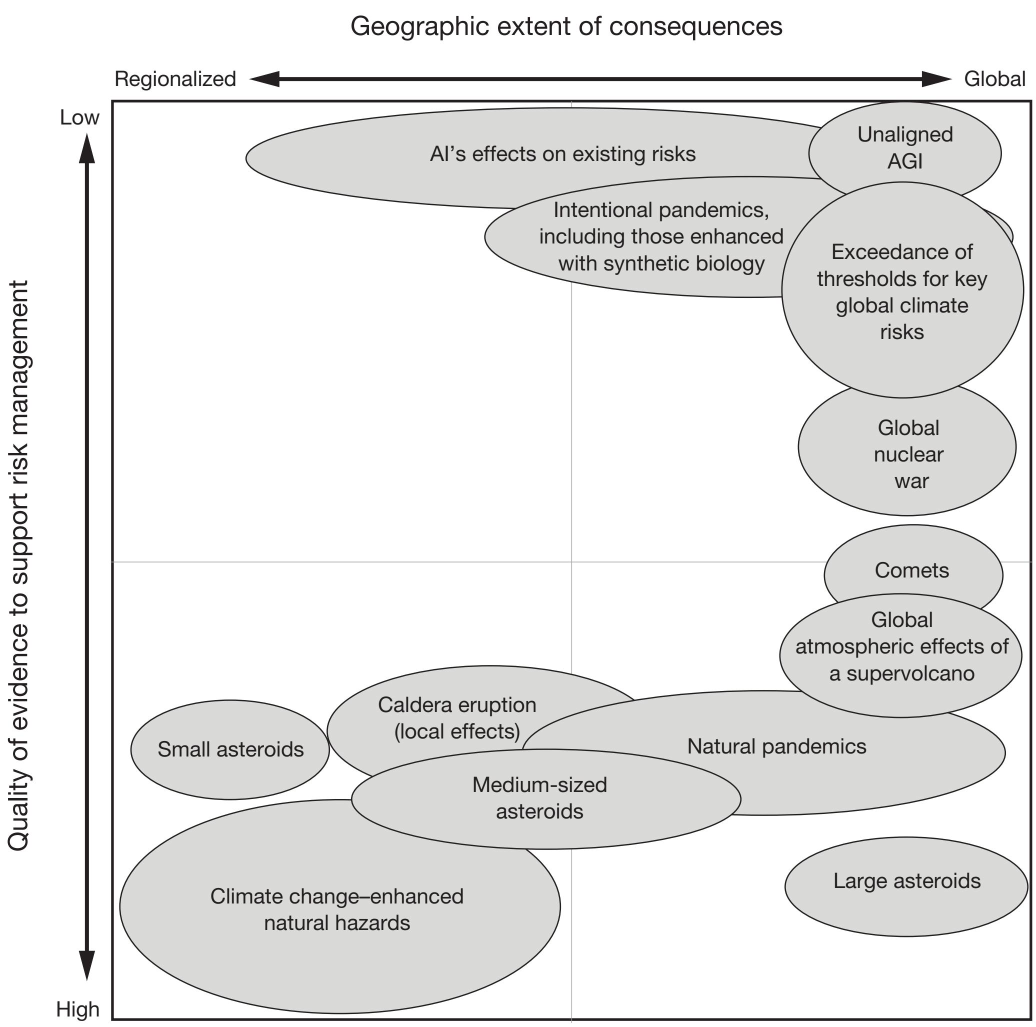
The Geographic Extent of Consequences and Quality of Evidence About Risks Offer Guidance for Appropriate Risk Management Strategies

The hazards and threats reviewed in this report can vary widely in terms of the geographic extent over which consequences can be expected to occur and the quality of understanding about their scope, likelihood, and consequences. These two dimensions of risk influence the appropriateness of risk management approaches.

Variation in Geographic Extent of Threat and Hazard Consequences

As shown in Figure 10.1, some hazards and threats would likely have regionalized consequences and would not be expected to overwhelm the capacity of a geographically larger country to respond and recover, although a geographically smaller country, if affected, might require regional assistance. Examples of such cases could

FIGURE 10.1
Quality of Evidence Supporting Risk Management and Geographic Extent of Risks for Global Catastrophic and Existential Risks



NOTE: The placement and size of the ovals in this figure represent a qualitative depiction of the relative relationships among threats and hazards based on interpretation of aspects of the assessments described in Chapters 4 through 9. The figure presents only examples of cases or scenarios described in those chapters, not all scenarios described.

include the blast and thermal effects associated with impact of an asteroid 50 m to 140 m in diameter or the effects of hurricanes made more intense or more frequent by climate change. For these types of events, countries develop plans to mitigate damage, warn populations, respond to incidents, and aid neighboring countries or regions with recovery should disaster strike.

As the geographic extent of threat and hazard consequences expands, so does the span of events and considerations that countries account for in risk management. Larger events could affect a country's interests beyond the localized areas where disaster strikes. Nuclear conflict anywhere in the world could destabilize economies and heighten conflicts that threaten friends and allies. A disease outbreak or bioterrorism, even if contained or involving a noninfectious agent, demands responses that affect trade, travel, and migration. Climate change–enhanced natural disasters could overwhelm some countries' responses, demanding foreign assistance and aid for recovery. For threats and hazards like these, with consequences that extend more broadly, countries plan both to contain the cascading consequences of events when they occur and to fulfill global responsibilities to help others and address risks when they do spread globally.

Events of the largest scale described in this report have global consequences or effects that are not contained geographically. Asteroids larger than 1,000 m in diameter, the largest supervolcanoes, runaway climate change, and global nuclear war hold the potential to affect all countries and all people. Advances in AI, although poorly defined and understood, have the potential to transform human civilization globally.

The geographic scale of the consequences of a risk is not the same as the geographic scale of the most-appropriate responses to a risk. Many of the risks shown in Figure 10.1 might be best addressed with a coordinated global response to most effectively prevent or address the consequences regardless of where disaster strikes.

Variation in Understanding of Threats and Hazards

Some of the threats and hazards described in this report are relatively well understood, with high consensus on the conditions that define them. For threats and hazards of this kind, theories, observation, and models explain with high confidence the processes by which exposure to the threat or hazard leads to harm. History and anticipatory models can inform estimates of how likely future events will be. For example, the processes by which floods, droughts, heat waves, and hurricanes cause damage can be characterized well enough to afford this level of understanding, even if the future magnitude and frequency of these events deviate significantly from this historical record. Supervolcanoes and asteroids, although infrequent, result from processes that are well understood. All these hazards are the result of natural processes, which might be changing but tend to follow natural and physical processes that are understood.

Other threats and hazards are dominated by the behavior of complex systems, which can be observed but not predicted. For some hazards, the complexity derives from human behaviors. Will a terrorist synthesize smallpox virus and use it to kill? Will nuclear conflict occur between regional adversaries? Or between global superpowers? The immediate consequences of these types of events can be modeled with relative certainty. And attempts have been made to forecast the likelihood of these types of events occurring. But reliably and accurately estimating the likelihood that a person, group, or country would initiate an attack of any of these types is not possible.

For other threats and hazards, biophysical systems display complex system behaviors. For example, some models of climate change suggest the potential for natural systems to shift to different equilibria, including disruption of oceanic and atmospheric circulation cycles. Whether at all or at what thresholds such changes would occur is deeply uncertain. How, whether, and when AGI might reach capabilities that threaten humans remain subjects of serious debate. Threats of this nature defy attempts at characterization beyond scenario descriptions.

Aligning Risk Management to the Nature of Specific Hazards

For the threats and hazards with relatively well-understood effects and response and where the geographic scale of the consequences aligns with the appropriate risk management jurisdictions (i.e., those in the lower left-hand corner of Figure 10.1—FEMA, DHS, and other parts of the U.S. government could begin to organize useful responses. For extreme climate events, such as larger or more-frequent hurricanes, the government could pursue a climate resilience strategy as described in the NCA5, *National Climate Resilience Framework*, and other reports.[5] For small asteroids, the government could improve NASA's planetary defense capabilities and improve capabilities for evacuation and civil defense. Such evacuation and civil defense capabilities would also prove useful for the local effects of a supervolcano of Yellowstone scale and for a limited nuclear attack. Other events of this scale and relative understanding can leverage existing planning frameworks, such as the National Preparedness System and conventional approaches to planning for continuity of government and continuity of operations.

Addressing the risks in the other corners of Figure 10.1, however, will require significant innovation to generate (1) the capacity for currently unknown or unavailable responses, (2) risk management approaches suitable for such deeply uncertain risks, and (3) enhanced institutions at all levels of governance (including internationally) able to implement these responses and risk management approaches. Such innovation in responses, approaches, and institutions could also enhance risk reduction for the better-understood risks in the lower left-hand corner of Figure 10.1.

An understanding of the specific response and institutional enhancements needed to manage these global catastrophic risks will require research. But considerations of risk management alternatives can help guide such research and the actions for implementation that derive from it:

- First, managing these risks will require a *portfolio approach* with multiple actions operating in synergy. Some actions, such as those focused on societal resilience, government capacity, and civil defense, will provide benefits for many—possibly all—of the global catastrophic risks. Other actions, such as the ability to deflect an extraterrestrial object headed toward Earth, will require a tailored capability with little utility for other risks. Portfolios of responses—in particular, those that emphasize as much as possible actions that address multiple risks—would reduce the overall costs of risk reduction and offer resilience to surprise by potentially providing some reduction in unanticipated risks.
- Second, reducing these global catastrophic risks will require *collective action* among many independent yet interdependent actors. Within the U.S. government, managing these risks will require a whole-of-government approach and improved collaboration among agencies and among federal, state, and local governments. More broadly, managing these risks will require improved polycentric governance among national governments, the private sector, and civil society.[6]
- Third, these risks require management approaches aligned with the *deep uncertainty* about the relevant threats and hazards, their consequences, and the interactions among them. Such approaches will require scenario development that reflects the uncertainties that could lead to a wide variety of future conditions and stress-testing proposed portfolios of risk management actions against a wide array of plausible scenarios to identify potential weaknesses and sensitivities to misspecified assumptions. In addition, such approaches will also require explicitly paying attention to how portfolios of actions might be designed to adjust over time to new information. Rather than seeking optimal strategies, risk management approaches should employ strategies that are robust for a wide assortment of scenarios.

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[5] Crimmins et al., *Fifth National Climate Assessment*; White House, *National Climate Resilience Framework*.

[6] *Polycentric governance* refers to conditions in which many formally independent centers of partial authority collectively cover the full array of governance tasks (Ostrom, "Beyond Markets and States").

- Fourth, risk management approaches addressing global risks in the face of deep uncertainty need to recognize the *diversity of values, objectives, and expectations* different communities will bring to judge alternative responses. Thus, risk management approaches should address both distributive justice and procedural justice. This requires that, to the extent possible, risk management approaches be developed using deliberative processes attentive to multiple voices and the distribution of consequences across communities.

These risk management observations framed by the assessments of the geographic extent and uncertainty about global catastrophic and existential risk provide a context within which to consider approaches to mitigate the threats they pose to civilization.

Risk Management and Global Catastrophic and Existential Risks

The long-term future of human civilization depends on the ability to manage risks posed by global catastrophic and existential risks. Although this study focused on risk assessment, not management, themes observed across the six risk assessments provide insights for consideration of the latter. Chapters 4 through 9 each apply M. Granger Morgan's framework for risk mitigation, introduced in Chapter 3, to identify approaches that could be used to manage global catastrophic or human existential risks.

Generally, these risk management practices, summarized in Table 10.3, fall into two broad categories: (1) actions to prevent the occurrence of the threat or hazard and (2) actions to reduce the consequences of the event if it occurs. The first category involves Morgan's mitigation dimensions of reducing the likelihood of occurrence and disrupting the mechanisms leading to risk. The second category involves those dimensions of reducing the severity of the consequences of a catastrophe and enhancing response and recovery options. As discussed in Chapter 3, risks to human civilizations arise from failures to mitigate risk or from risks stemming from adopting precautionary interventions that impede beneficial activities associated with the threats and hazards involved. In this section, we discuss the maturity of the various approaches to managing the risks assessed in this report.

Preventing the Effect

The existing ability to prevent the effect of an assessed threat or hazard is at different stages of development and capability for different threats and hazards. For the least mature cases, there are theoretical and untested approaches to mitigate the risk. This includes such approaches as draining heat from the magma chamber of or a controlled release of magma from a supervolcano. Likewise, in-space deflection or disruption approaches for large impactor asteroids and comets are also largely untested and rely on timing of detection and the impactor's distance to Earth. Thus far, NASA has tested only one possible approach.

Although the existing and future threats to AI remain uncertain, governmental and nongovernmental organizations have produced frameworks to help identify characteristics of trustworthy AI to prevent the deployment of systems that could cause harm. The AI community has also proposed risk management strategies, such as international technical standards, regulations, voluntary self-regulation, and market pressures. The exact construct and substance of these strategies will depend on the ongoing development of uses of AI.

Next are risk management approaches that might be well studied, tested, and mature but largely depend on influencing human behaviors and ways of life. These include curtailing GHG emissions or geoengineering to reduce the progression of climate change and the uptake of effective hygiene practices coupled with research, development, and acceptance of vaccines to prevent a catastrophic pandemic. Preventing nuclear war also falls into this category because it predicting when a nuclear-capable actor might choose to use these

TABLE 10.3

Hazard Mitigation Approaches, by Mitigation Dimension and by Threat or Hazard

Mitigation Dimension	Hazard Mitigation Approach					
	AI	Asteroid or Comet Impact	Nuclear War	Climate Change	Severe Pandemic	Supervolcanoes
Reduce the likelihood of occurrence.	• Develop safe, secure, and trustworthy AI systems. • Pause AI development until safety protocols are established.	• Try one or more experimental approaches of in-space deflection or disruption of threatening objects enabled by early detection of impactors.	• Reduce international tensions; reduce the number and power of nuclear weapons.	• Exercise one or more of the extensive technological, regulatory, and behavioral options to monitor and slow the accumulation of greenhouse gases in the atmosphere.	• Reduce human activities that contribute to naturally occurring, accidentally laboratory-induced, or deliberately caused pandemics, and reduce susceptibility through vaccination against the likeliest threats.	• Highly speculative options have been proposed, but no credible options are known.
Disrupt the mechanisms leading to risk.	• Oversee AI to determine risk for specific contexts. • Continue human oversight of AI decisions in high-risk domains. • Engage in postdeployment performance monitoring.	• Try one or more experimental approaches of in-space deflection or disruption of threatening objects enabled by early detection of impactors.	• Engage counterforce for damage limitation and use active (air and missile) defenses.	• Exercise one or more experimental geoengineering options to offset radiative forcing and remove or sequester carbon dioxide.	• Reduce pandemic risk by addressing habitat encroachment, unsafe lab experiments, and misuse of technology.	• Highly speculative options have been proposed, but no credible options are known.
Reduce the severity of effects.	• Retain the ability to modify or roll back AI systems in case of adverse outcomes.	• Try one or more experimental approaches of in-space disruption of impactors, large-scale evacuations, timely public warning, and increasing human civilization's resilience.	• Engage in civil defense (e.g., bomb shelters, evacuation, dispersal of potential targets).	• Exercise one or more of the extensive technological, regulatory, and behavioral options to avoid, reduce, or spread the risks that climate change poses to society; their deployment capacity varies.	• Develop pandemic preparedness measures, and increase confidence in government institutions responsible for pandemic planning and response.	• Issue warnings and conduct large-scale evacuations. • Exercise one or more theoretical, untested geoengineering options, such as containing erupted material with stratospheric tents or sky bots and injecting greenhouse agents into the stratosphere.
Enhance response and recovery.	• This is not applicable, given the uncertainty about potential pathways and outcomes.	• Coordinate planetary defense efforts. • Prepare terrestrial responses (e.g., evacuations). • Increase human civilization's resilience.	• Stockpile food and medical supplies; make continuity-of-government arrangements.	• Scale up existing response and recovery options to mitigate societal risks.	• Shorten timelines for development of medical countermeasures. • Improve strategic communications.	• Provide for disaster recovery, population evacuations, and developing replacement resources to sustain populations. • Coordinate and communicate observations and warnings.

weapons in a conflict or to negotiate a reduction in the number and power of nuclear weapons is difficult. Although the principle of mutually assured destruction is presented as an effective deterrent, some doubt the robustness of this approach to risk management. Countries can also build or enhance their capabilities in active defense to prevent a nuclear weapon from reaching its intended target.

Reducing Consequences of Effect

Strategies to reduce the severity of the effects of the assessed threats and hazards also vary but can closely align with existing frameworks (e.g., DHS's National Preparedness System and National Planning Frameworks) when considering response and recovery options,[7] although the most-salient approaches are determined by characteristics of the risks posed by each threat or hazard. Reducing the consequences of climate change or nuclear war involves building resilience in affected or potentially affected communities through such actions as reducing exposure to climate hazards by, for example, relocating at-risk populations or building shelters. Preparing for a supervolcano or a large asteroid impact can take a similar approach through evacuation planning. These approaches will require significant investment in governments' and communities' research and development of early-warning systems and preparedness planning. Furthermore, reducing the severity of pandemics will require more than accelerated vaccine development and administration. Recent examples of vaccine hesitation and mistrust among the public illustrate that government institutions will also need to gain the confidence of their respective communities and improve their strategic communication. All these examples depend on deliberative governance processes and organization supported by technical and human resources to gain legitimacy and trust among the public.

Three Types of Risk Mitigation Efforts: Taking Action, Governing, and Learning

The approaches summarized in Table 10.3 include three ways in which society can advance risk management: acting, governing, and learning. Many of the approaches described involved technical or logistical measures that can be implemented to intervene in ways that prevent or reduce risks. Others involve using regulations and laws, policies, or norms to influence actions and behaviors in ways that reduce risks. Finally, for some hazards, there might not be options or enough knowledge about risks to either act or govern, and research and development are necessary before more-active steps can be taken. Looking at the risks from this perspective provides insights into which organizations and sectors are critical to managing global catastrophic and existential risks and how they can contribute.

Given the gravity of potential consequences of the threats and hazards assessed in this report, it is both fortunate and unsurprising that there are many ways in which people can work to manage the resulting risks. Figure 10.2 summarizes the approaches presented in Table 10.3 in terms of the applicability of steps involving technical and logistical solutions (acting), governance and policy approaches (governing), and research and development efforts (learning).

Technical and logistical approaches are most relevant for those threats and hazards that are better understood and for which solutions are readily available, such as managing the effects of nuclear detonations, natural hazards enhanced by climate change, pandemics, and efforts involving public warnings, evacuations, and incident response and recovery. Technical and logistical options exist for all threats and hazards except for the catastrophic and existential risk from AI. Although technical and logistical solutions can directly reduce risk, they can also be costly and require attention to planning and evaluation to ensure effective implementation.

[7] FEMA, "National Preparedness System"; FEMA, "National Planning Frameworks."

FIGURE 10.2

Types of Approaches Available to Manage Global Catastrophic and Human Existential Risks, by Mitigation Dimension and by Threat or Hazard

	AI	Asteroid and Comet Impact	Nuclear War	Climate Change	Severe Pandemic	Super-volcanoes
Reduce the likelihood of occurrence.	Governance and policy, Research and development	Research and development	Governance and policy, Technical and logistical	Governance and policy, Technical and logistical, Research and development	Governance and policy, Technical and logistical, Research and development	Research and development
Disrupt the mechanisms leading to the risk.	Governance and policy, Research and development	Research and development	Governance and policy, Technical and logistical	Research and development	Governance and policy, Technical and logistical, Research and development	Research and development
Reduce the severity of the effects.	Governance and policy, Research and development	Governance and policy, Technical and logistical, Research and development	Governance and policy, Technical and logistical	Governance and policy, Technical and logistical	Governance and policy, Technical and logistical, Research and development	Governance and policy, Technical and logistical, Research and development
Enhance response and recovery.	Not applicable	Governance and policy, Technical and logistical	Governance and policy, Technical and logistical	Governance and policy, Technical and logistical	Governance and policy, Technical and logistical, Research and development	Governance and policy, Technical and logistical

Governance and policy | Technical and logistical | Research and development

Governance and policy approaches are relevant where risks result from human behaviors and economic activity. Regulations and policies can be established to prevent or minimize the misuse or development of dangerous AI and biotechnology, reduce emissions of carbon into the atmosphere, reduce tensions that could lead to nuclear war or the number of nuclear weapons held globally, and coordinate national or global efforts to warn populations of threats and hazards and to respond or support recovery should incidents occur. Like technical and logistical approaches, governance and policy can reduce risks directly. However, governance and policy depend on legal and political systems for successful implementation.

In two cases, research and development present opportunities to identify new approaches to manage risks to human civilization and existence. In some instances, the processes leading to risk or availability of feasible, proven approaches to managing risks are just unknown. For example, although the ways in which asteroids, comets, supervolcanoes, and increasing concentrations in atmospheric carbon pose harms are understood, approaches to reducing the likelihood of occurrence or disrupting mechanisms leading to risk by deflecting asteroids, venting volcanoes, and sequestering atmospheric carbon are only theorized or experimental. In other instances, advances in technology present options to reduce risks. For example, advances in biotechnology and AI hold the potential to create new vaccines and MCMs that are more effective and developed on shorter timelines. And research on AI safety and security could inform governance and AI development to mitigate risks of misuse or development of unaligned AGI.

Viewing risk management approaches through this lens of acting, governing, and learning (Figure 10.2) provides a mechanism to organize the approaches listed in Table 10.3 for policymakers who are seeking to understand or are responsible for implementing options under each type of risk mitigation approach.

Recommendations

The six risk assessments presented in this report paint a complex picture of global catastrophic and human existential risk that demands an approach to risk management that matches the nature of these threats and hazards, the uncertainties that surround them, and the interactions among them. To do so, the United States and other countries should consider taking several steps toward improving assessment and management of threats and hazards that present the potential for global catastrophic and existential risks:

- **Incorporate comprehensive risk assessments into management of global catastrophic and existential risks.** As described in Chapters 2 and 3, assessments of catastrophic risk should consider the many types of consequences that these threats and hazards impose on society. These include assessment of mortality, effects on ecosystem and societal stability, and reductions in human capabilities. Assessments should also consider how other aspects of risk, such as uncertainty and distribution of effects among communities and generations, influence priorities. Managing this diverse set of threats and hazards requires a portfolio of risk management strategies that covers the full span of risks; incorporate approaches to reduce both the likelihood of threats and hazards and their consequences; and are flexible to changes in conditions that generate risks, adaptive to uncertainty about the risks, and robust to changes in risk over time or challenges faced when multiple risks threaten society. Addressing these risks also demands recognition of the diversity of values and perspectives that motivate concerns about risk and influence prioritization of risk management efforts and inclusive incorporation of communities into deliberations about risk management decisionmaking. The risk assessments presented in this report adopt this approach and provide a starting point for improving risk assessment and management of risks that threaten civilization.
- **Develop a coordinated and expanded federally funded research agenda to reduce uncertainty about global catastrophic and existential risks and to improve the capability to manage such risks.** The risk assessments related to specific threats and hazards presented in this report describe questions that remain about how events will occur, what their consequences will be should they occur, and what options exist to reduce these risks. The types and nature of these uncertainties are described in Chapters 4 through 9 and summarized in Tables 10.1 and 10.2. Engagement of international scientific and policy communities can help (1) identify productive avenues for natural, physical, and social science research to answer these questions and improve understanding of the processes generating global catastrophe risks and (2) identify novel approaches to reduce either the likelihood or the consequences of these threats and hazards. Expanded research will necessarily be multidisciplinary and internationally collaborative, and funding must be coordinated across federal government agencies. The first step in reducing uncertainty is to begin broad, multidisciplinary, multisector engagement to shape the research agenda being pursued. Areas of investigation can improve understanding of basic physical and natural processes leading to risk or determining effectiveness of mitigation; greater understanding and identification of populations most vulnerable and least resilient globally and how people perceive and respond to risks and options to manage them individually and collectively; and understanding of how trends in technology will shape future risks or can be leveraged to manage them. However, even with additional research, some uncertainty about global catastrophic and existential risks will remain irresolvable.
- **Develop plans and strategies when global catastrophic and existential risk assessments are supported with adequate evidence.** This is possible when science about the phenomena leading to risk are well understood and the consequences are relatively limited in the context of global catastrophe, even if they exceed the magnitude of events typically addressed in planning. These conditions exist for threats and hazards in the lower-left quadrant in Figure 10.1, such as smaller asteroids, regional effects of volcanic eruptions, and natural hazards that could be enhanced by climate change. In such cases, countries

should utilize existing risk management approaches. For example, risk management plans for events that do not exceed national response capacity should be developed and tested using national response frameworks, if such plans do not already exist. And, if they do, countries should review and test the plans against the risks described in this report. For risks in the lower-right quadrant of Figure 10.1—such as pandemics, global effects of very large eruptions, and impacts of larger asteroids—international engagement and collaboration will be essential to risk management strategies and plans.

- **Expand international dialogue and collaboration that addresses global catastrophic and existential risks.** In the context of events described in this report that require a global response, risks can be managed through global coordination mechanisms, such as nongovernmental organizations and international treaties and agreements. These conditions become relevant for threats and hazards associated with the right side of the horizontal axis in Figure 10.1, such as pandemics, larger asteroid and comet impacts, global effects of volcanic eruptions, global nuclear war, effects of exceeding key global climate thresholds, and risks resulting from AGI development. Threat and hazard monitoring is a key aspect of global risk management identified in the six risk assessments presented in this report. Maintaining and sharing awareness of changes in or emergence of new sources of these threats and hazards is required to enable planning and implementation of coordinated and effective risk management strategies. Where global monitoring and planning structures do not exist or are not widely recognized, consideration should be given to how existing international cooperation bodies and structures could be used or expanded to address concerns of global catastrophes. Where they do exist, they might still require adjustments to reflect specific elements associated with the emerging nature of some global catastrophic and existential risks.
- **Adapt planning and strategy development to address irresolvable uncertainties about global catastrophic and existential risks.** To account for unresolvable uncertainties, such as those described in this report, planning efforts must envision a wide variety of plausible scenarios that could threaten human civilization and test risk management strategies across these scenarios to identify potential weaknesses and opportunities. Planning and strategy developers should augment conventional risk management frameworks with tools adapted to address emerging risks, such as future analysis, decisionmaking under deep uncertainty, scenario planning, and games and exercises that include planners and policymakers. These approaches are especially relevant for threats and hazards associated with the top of the vertical axis in Figure 10.1, such as risks from AI, extreme climate change, and intentional pandemics.

The GCRMA recognizes the importance of understanding the potential for global catastrophe and human extinction and taking prudent steps to protect the world against these risks. The risk assessments presented in this report summarize current understanding of a selection of these threats and hazards. Placing these assessments in the context of risk governance and risk management serves as a first step in this process. Only continued attention, inquiry, and action will ensure that society is able to protect human civilization where opportunities to do so exist and build a more resilient and prepared society should a global catastrophe occur.

APPENDIX A

Literature Search Strategy

This appendix describes the search strategy we used to identify published studies assessing the risks of the threats and hazards described in Chapters 4 through 9 of this report. Search strategies were formulated for the databases shown in Table A.1. We applied the following parameters to each search strategy:

- articles in peer-reviewed literature
- available in English
- published between January 2013 and September 2023.

We constructed and reviewed the primary search strategy for Web of Science databases before finalizing it and translating for the other databases using their specific syntax and subject headings (controlled terminology). After revising the primary search, we ran all database searches on September 11, 2023. We developed the search strategy using the following six threats with catastrophic or existential risks:

- pandemics (including bioterrorism)
- nuclear war
- asteroids (including meteors) and comets
- supervolcanoes
- extreme climate change
- AI.

To increase specificity of search results and decrease the number of irrelevant results to screen, we combined these blocks (search strings) with search strings for the concepts of risk assessment, catastrophic and existential risks, and global catastrophes.

We saved all database search results as Research Information Systems (RIS) files then imported them into an EndNote library for deduplication of records. The custom 1 field was added to the records to include such details as which database the citation was from, the threat, and the search date. Results were exported from Clarivate EndNote into Microsoft Excel and delivered to each of the six teams assigned to review the literature. Tables A.2 through A.5 provide the search terms and resulting number of identified references for each threat or hazard.

TABLE A.1

Databases Searched

Product, in Order of Completed Search	Publisher	Collection	Index
Web of Science	Clarivate	Core Collection	Emerging Sources Citation Index
			Social Sciences Citation Index
			Science Citation Index–Expanded
		Preprint Citation Index	
Scopus	Elsevier		
Academic Search Complete	EBSCO		
Policy File Index[a]	ProQuest		
Homeland Security Digital Library[a]	Naval Postgraduate School Center for Homeland Defense and Security and FEMA		
Google Search (site:.gov)[a]	Google		

[a] Gray literature.

TABLE A.2

Web of Science Core Collection Literature Search and Results

Set	Search	Number of Results
1 Risk assessment	**TS=**((risk* OR threat*) NEAR/3 (analy* OR assess* OR avert* OR avoid* OR detect* OR estimat* OR evaluat* OR foresight* OR framework* OR likelihood* OR manag* OR measur* OR mitigat* OR model* OR monitor* OR predict* OR prevent* OR probabilit* OR surveill* OR stochastic*))	823,884
2 Catastrophic or existential risks	**TS=**((catastroph* OR existential) NEAR/1 (risk* OR threat*))	2,774
3 Global catastrophes	**TS=**("global catastroph*" OR GCR* OR "doomsday scenario*" OR apocalyp* OR armageddon OR omnicid* OR (existential NEAR/1 catastroph*) OR ((human* OR planet*) NEAR/2 (extinction* OR decimat*)) OR (world NEAR/2 end) OR ((catastroph* OR existential OR cataclysm* OR "life ending*") NEAR/1 threat*) OR (extinction NEAR/1 risk*) OR megacatastroph* OR "mega catastroph*" OR ((mass* OR complete OR full OR total OR global OR catastroph*) NEAR/1 (collaps* OR extinction* OR destruct* OR devastat* OR obliterat* OR annihilat* OR decimat* OR morality OR "death toll*" OR famine* OR disaster* OR eradicat*)) OR ((environmental OR ecosystem* OR "eco system*" OR social OR societ* OR humanit* OR civilis* OR civiliz* OR anthropogenic) NEAR/1 (collaps* OR catastroph* OR cataclysm*)) OR "abrupt sunlight reduction*" OR ASRS* OR ((food* OR water* OR agricultur* OR telecommunicat* OR electric*) NEAR/1 (system* OR supply OR chain* OR "breadbasket" OR "bread basket" OR infrastructure* OR "infra structure*" OR "industrial control*") NEAR/2 (fail* OR collaps* OR crisis OR scarcity OR contaminat* OR disrupt*)) OR ((nuclear OR impact OR volcanic) NEAR/1 winter) OR (CBRN* AND (catastroph* OR risk*)))	56,487
4	((#1 OR #2) AND **#3**) AND (PY==("2013" OR "2014" OR "2015" OR "2016" OR "2017" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023") AND DT==("ARTICLE" OR "REVIEW" OR "EARLY ACCESS") AND LA==("ENGLISH"))	3,669

Table A.2—Continued

Set	Search	Number of Results
5 Pandemics and bioterrorism	**TS=**(bioterror* OR “bio terror*” OR “biological warfare*” OR biowarfare OR “bio warfare” OR (biological NEAR/1 attack*) OR “biological weapon*” OR bioweapon* OR “bio weapon*” OR “biological agent*” OR “bio agent*” OR “global catastrophic biological risk*” OR GCBR* OR biosecurity OR “chemical weapon*” OR CBRN* OR ((synthetic OR “human manufactur*” OR “man made” OR modif* OR weaponiz* OR manipulat* OR chimer* OR engineered OR catastroph*) NEAR/2 (virus* OR viral OR bacter* OR mycosis OR mycotic OR fungi OR fungal OR pandemic* OR pathogen* OR toxin* OR “harmful agent*” OR “lethal agent*”)) OR ((severe OR extreme OR sudden OR global OR mass* OR catastroph* OR disaster*) NEAR/2 (pandemic* OR “global public health” OR epidemic* OR outbreak* OR plague*)))	91,546
6 Nuclear war	**TS**=(((nuclear OR thermonuclear OR “thermo nuclear” OR radioactive) NEAR/2 (war* OR strike* OR attack* OR missile* OR weapon* OR bomb* OR destruct* OR terrori* OR explosion* OR catastroph* OR annihilat*)) OR CBRN* OR “nuclear winter*” OR “high altitude electromagnetic pulse*” OR “high altitude electro magnetic pulse*” OR (weapon* NEAR/1 “mass destruction”) OR “intercontinental ballistic missile*” OR ((nuclear OR radioactive) NEAR/2 (fallout OR waste*)))	38,414
7 Asteroids and meteors	**TS=**(asteroid* OR comet* OR meteor* OR bolide* OR superbolide* OR “planetary defense*” OR “planetary defence*” OR “near earth object*” OR NEO* OR ((astronomical OR interstellar OR cosmic OR extraterrestrial OR stellar) NEAR/1 (threat* OR impact* OR collision* OR object*)) OR ((“near earth” OR “potentially hazardous” OR “large crater forming” OR fireball* OR “impact event*” OR “impact risk*” OR “impact winter*” OR “earth crossing*” OR “planet destroy*” OR “planet sterili*” OR catastroph*) NEAR/1 (asteroid* OR meteor* OR bolide* OR comet*)))	1,364,742
8 Supervolcanoes	**TS=**(“super volcan*” OR “massive volcan*” OR supervolcan* OR megavolcan* OR “mega volcan*” OR “large igneous province*” OR (massive NEAR/1 eruption*) OR (super NEAR/1 eruption*) OR “supereruption*” OR (mega NEAR/1 eruption*) OR (eruption* NEAR/2 (“large magnitude” OR “magnitude 8” OR M8)) OR (“flood basalt” NEAR/2 (erupt* OR event*)) OR ((flood OR massive OR super OR mega OR floor) NEAR/2 (“lava erupt*” OR “lava event*”)) OR “volcanic winter*” OR (volcan* NEAR/2 (“oceanic anoxic event*” OR euxin* OR catastroph*)))	5,206
9 Extreme climate change	**TS=**(((severe OR extreme OR sudden OR abrupt* OR global OR mass* OR catastroph* OR disaster* OR runaway) NEAR/1 (“climate change*” OR “global warming” OR “natural disaster*”)) OR ((climat* OR ecosystem* OR “eco system*”) NEAR/1 (catastroph* OR disaster* OR collaps*)) OR (environment* NEAR/1 devastation) OR “extreme temperature change*” OR (disruption* NEAR/2 (“global oceanic” OR “global atmospheric current*”)) OR (climate NEAR/2 (“global oceanic” OR “global atmospher* current*”)) OR ((evaporat* OR melt* OR collapse*) NEAR/1 (“global ocean*” OR “sea ice” OR glacier* OR “ice cap*” OR “ice sheet*”)) OR “melt* water” OR meltwater OR (“extreme weather” NEAR/2 (acidif* OR deoxygen*)) OR (“global ocean*” NEAR/1 (anox* OR euxin*)) OR (ocean* NEAR/1 (“temperature change*” OR warming)) OR ((rapid OR extreme) NEAR/1 rise* NEAR/1 (“sea level*” OR “ocean level*”)))	115,552
10 AI threats	**TS**=((“artificial intelligence” OR “AI” OR “artificial general intelligence” OR “super intelligen*” OR superintelligen* OR “machine learning” OR “machine intelligence” OR “computational intelligence” OR “deep learning” OR singularity OR GPT* OR “generative pre trained transformer*” OR “generative artificial intelligence” OR “generative AI” OR ChatGPT* OR GPT* OR “Open AI” OR OpenAI OR ((autonomous OR automated) NEAR/2 (militar* OR weapon*)) OR cyborg* OR robot* OR “bot” OR “bots” OR “auto catastroph*” OR “human artificial intelligence hybrid*” OR ((human* OR biologic*) NEAR/2 (“artificial intelligence” OR “machine intelligence”)) OR (Google NEAR/1 Bard) OR “LLaMA” OR ((artificial OR computer*) NEAR/1 “neural net*”)) AND (terror* OR “take over*” OR takeover* OR provok* OR weapon* OR hack* OR catastrop* OR apocalyp* OR threat* OR attack* OR harm* OR adversar* OR offens* OR disrupt* OR ((data OR information) NEAR/2 (poison* OR corrupt* OR manipulat*)) OR “decisive strategic advantage” OR “instrumental convergence” OR “intelligence explosion*” OR “AI safety” OR “AI security” OR ((generat* OR creat* OR disseminat* OR deploy*) NEAR/2 (disinformation OR misinformation OR “fake content” OR “deep fake*” OR deepfake*))))	47,532

Table A.2—Continued

Set	Search	Number of Results
11 AI only	**TS**=("artificial intelligence" OR "AI" OR "artificial general intelligence" OR "super intelligen*" OR superintelligen* OR "machine learning" OR "machine intelligence" OR "computational intelligence" OR "deep learning" OR singularity OR GPT* OR "generative pre trained transformer*" OR "generative artificial intelligence" OR "generative AI" OR ChatGPT* OR GPT* OR "Open AI" OR OpenAI OR ((autonomous OR automated) NEAR/2 (militar* OR weapon*)) OR cyborg* OR robot* OR "bot" OR "bots" OR "auto catastroph*" OR "human artificial intelligence hybrid*" OR ((human* OR biologic*) NEAR/2 ("artificial intelligence" OR "machine intelligence")) OR (Google NEAR/1 Bard) OR "LLaMA" OR ((artificial OR computer*) NEAR/1 "neural net*"))	829,733
12 All threats	#5 OR #6 OR #7 OR #8 OR #9 OR #10	1,650,403
13 All threats and risk assessments	#4 AND #12 AND (PY==("2013" OR "2014" OR "2015" OR "2016" OR "2017" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023") AND LA==("ENGLISH") AND DT==("ARTICLE" OR "REVIEW" OR "EARLY ACCESS"))	625
14 Pandemics and bioterrorism	(#4 AND **#5**) AND (PY==("2013" OR "2014" OR "2015" OR "2016" OR "2017" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023") AND DT==("ARTICLE" OR "REVIEW" OR "EARLY ACCESS") AND LA==("ENGLISH"))	108
15 Nuclear war	(#4 AND **#6**) AND (PY==("2013" OR "2014" OR "2015" OR "2016" OR "2017" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023") AND DT==("ARTICLE" OR "REVIEW" OR "EARLY ACCESS") AND LA==("ENGLISH"))	114
16 Asteroids	(#4 AND **#7**) AND (PY==("2013" OR "2014" OR "2015" OR "2016" OR "2017" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023") AND DT==("ARTICLE" OR "REVIEW" OR "EARLY ACCESS") AND LA==("ENGLISH"))	178
17 Supervolcanoes	(#4 AND **#8**) AND (PY==("2013" OR "2014" OR "2015" OR "2016" OR "2017" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023") AND DT==("ARTICLE" OR "REVIEW" OR "EARLY ACCESS") AND LA==("ENGLISH"))	16
18 Climate change	(#4 AND **#9**) AND (PY==("2013" OR "2014" OR "2015" OR "2016" OR "2017" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023") AND DT==("ARTICLE" OR "REVIEW" OR "EARLY ACCESS") AND LA==("ENGLISH"))	251
19 AI	(#4 AND **#10**) AND (PY==("2013" OR "2014" OR "2015" OR "2016" OR "2017" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023") AND DT==("ARTICLE" OR "REVIEW" OR "EARLY ACCESS") AND LA==("ENGLISH"))	88
Subsets		
Catastrophic risk assessment, all threats, and AI *only*	#11 AND #13	92
Catastrophic risk assessment, pandemics, and AI *only*	#11 AND #14	6
Nuclear war and AI *only*	#11 AND #15	10

NOTE: This search included Emerging Sources Citation Index, Science Citation Index–Expanded, and Social Sciences Citation Index.

TABLE A.3
Preprint Citation Index Literature Search and Results

Set	Search	Number of Results
1 Risk assessment	**TS=**((risk* OR threat*) NEAR/3 (analy* OR assess* OR avert* OR avoid* OR detect* OR estimat* OR evaluat* OR foresight* OR framework* OR likelihood* OR manag* OR measur* OR mitigat* OR model* OR monitor* OR predict* OR prevent* OR probabilit* OR surveill* OR stochastic*))	12,420
2 Catastrophic or existential risks	**TS=**((catastroph* OR existential) NEAR/1 (risk* OR threat*))	83
3 Global catastrophes	**TS=**(“global catastroph*” OR GCR* OR “doomsday scenario*” OR apocalyp* OR armageddon OR omnicid* OR (existential NEAR/1 catastroph*) OR ((human* OR planet*) NEAR/2 (extinction* OR decimat*)) OR (world NEAR/2 end) OR ((catastroph* OR existential OR cataclysm* OR “life ending*”) NEAR/1 threat*) OR (extinction NEAR/1 risk*) OR megacatastroph* OR “mega catastroph*” OR ((mass* OR complete OR full OR total OR global OR catastroph*) NEAR/1 (collaps* OR extinction* OR destruct* OR devastat* OR obliterat* OR annihilat* OR decimat* OR morality OR “death toll*” OR famine* OR disaster* OR eradicat*)) OR ((environmental OR ecosystem* OR “eco system*” OR social OR societ* OR humanit* OR civilis* OR civiliz* OR anthropogenic) NEAR/1 (collaps* OR catastroph* OR cataclysm*)) OR “abrupt sunlight reduction*” OR ASRS* OR ((food* OR water* OR agricultur* OR telecommunicat* OR electric*) NEAR/1 (system* OR supply OR chain* OR “breadbasket” OR “bread basket” OR infrastructure* OR “infra structure*” OR “industrial control*”) NEAR/2 (fail* OR collaps* OR crisis OR scarcity OR contaminat* OR disrupt*)) OR ((nuclear OR impact OR volcanic) NEAR/1 winter) OR (CBRN* AND (catastroph* OR risk*)))	2,285
4	(((#1 OR #2) AND #3)) AND (PY==(“2012” OR “2013” OR “2014” OR “2015” OR “2016” OR “2017” OR “2018” OR “2019” OR “2020” OR “2021” OR “2022” OR “2023”) AND LA==(“ENGLISH”))	108
5 Pandemics and bioterrorism	**TS=**(bioterror* OR “bio terror*” OR “biological warfare*” OR biowarfare OR “bio warfare” OR (biological NEAR/1 attack*) OR “biological weapon*” OR bioweapon* OR “bio weapon*” OR “biological agent*” OR “bio agent*” OR “global catastrophic biological risk*” OR GCBR* OR biosecurity OR “chemical weapon*” OR CBRN* OR ((synthetic OR “human manufactur*” OR “man made” OR modif* OR weaponiz* OR manipulat* OR chimer* OR engineered OR catastroph*) NEAR/2 (virus* OR viral OR bacter* OR mycosis OR mycotic OR fungi OR fungal OR pandemic* OR pathogen* OR toxin* OR “harmful agent*” OR “lethal agent*”)) OR ((severe OR extreme OR sudden OR global OR mass* OR catastroph* OR disaster*) NEAR/2 (pandemic* OR “global public health” OR epidemic* OR outbreak* OR plague*)))	2,248
6 Nuclear war	**TS**=(((nuclear OR thermonuclear OR “thermo nuclear” OR radioactive) NEAR/2 (war* OR strike* OR attack* OR missile* OR weapon* OR bomb* OR destruct* OR terrori* OR explosion* OR catastroph* OR annihilat*)) OR CBRN* OR “nuclear winter*” OR “high altitude electromagnetic pulse*” OR “high altitude electro magnetic pulse*” OR (weapon* NEAR/1 “mass destruction”) OR “intercontinental ballistic missile*” OR ((nuclear OR radioactive) NEAR/2 (fallout OR waste*)))	614
7 Asteroids and meteors	**TS=**(asteroid* OR comet* OR meteor* OR bolide* OR superbolide* OR “planetary defense*” OR “planetary defence*” OR “near earth object*” OR NEO* OR ((astronomical OR interstellar OR cosmic OR extraterrestrial OR stellar) NEAR/1 (threat* OR impact* OR collision* OR object*)) OR ((“near earth” OR “potentially hazardous” OR “large crater forming” OR fireball* OR “impact event*” OR “impact risk*” OR “impact winter*” OR “earth crossing*” OR “planet destroy*” OR “planet sterili*” OR catastroph*) NEAR/1 (asteroid* OR meteor* OR bolide* OR comet*)))	16,316
8 Supervolcanoes	**TS=**(“super volcan*” OR “massive volcan*” OR supervolcan* OR megavolcan* OR “mega volcan*” OR “large igneous province*” OR (massive NEAR/1 eruption*) OR (super NEAR/1 eruption*) OR “supereruption*” OR (mega NEAR/1 eruption*) OR (eruption* NEAR/2 (“large magnitude” OR “magnitude 8” OR M8)) OR (“flood basalt” NEAR/2 (erupt* OR event*)) OR ((flood OR massive OR super OR mega OR floor) NEAR/2 (“lava erupt*” OR “lava event*”)) OR “volcanic winter*” OR (volcan* NEAR/2 (“oceanic anoxic event*” OR euxin* OR catastroph*)))	22

Table A.3—Continued

Set	Search	Number of Results
9 Extreme climate change	**TS=**(((severe OR extreme OR sudden OR abrupt* OR global OR mass* OR catastroph* OR disaster* OR runaway) NEAR/1 ("climate change*" OR "global warming" OR "natural disaster*")) OR ((climat* OR ecosystem* OR "eco system*") NEAR/1 (catastroph* OR disaster* OR collaps*)) OR (environment* NEAR/1 devastation) OR "extreme temperature change*" OR (disruption* NEAR/2 ("global oceanic" OR "global atmospheric current*")) OR (climate NEAR/2 ("global oceanic" OR "global atmospher* current*")) OR ((evaporat* OR melt* OR collapse*) NEAR/1 ("global ocean*" OR "sea ice" OR glacier* OR "ice cap*" OR "ice sheet*")) OR "melt* water" OR meltwater OR ("extreme weather" NEAR/2 (acidif* OR deoxygen*)) OR ("global ocean*" NEAR/1 (anox* OR euxin*)) OR (ocean* NEAR/1 ("temperature change*" OR warming)) OR ((rapid OR extreme) NEAR/1 rise* NEAR/1 ("sea level*" OR "ocean level*")))	1,216
10 AI threats	**TS**=(("artificial intelligence" OR "AI" OR "artificial general intelligence" OR "super intelligen*" OR superintelligen* OR "machine learning" OR "machine intelligence" OR "computational intelligence" OR "deep learning" OR singularity OR GPT* OR "generative pre trained transformer*" OR "generative artificial intelligence" OR "generative AI" OR ChatGPT* OR GPT* OR "Open AI" OR OpenAI OR ((autonomous OR automated) NEAR/2 (militar* OR weapon*)) OR cyborg* OR robot* OR "bot" OR "bots" OR "auto catastroph*" OR "human artificial intelligence hybrid*" OR ((human* OR biologic*) NEAR/2 ("artificial intelligence" OR "machine intelligence")) OR (Google NEAR/1 Bard) OR "LLaMA" OR ((artificial OR computer*) NEAR/1 "neural net*")) AND (terror* OR "take over*" OR takeover* OR provok* OR weapon* OR hack* OR catastrop* OR apocalyp* OR threat* OR attack* OR harm* OR adversar* OR offens* OR disrupt* OR ((data OR information) NEAR/2 (poison* OR corrupt* OR manipulat*)) OR "decisive strategic advantage" OR "instrumental convergence" OR "intelligence explosion*" OR "AI safety" OR "AI security" OR ((generat* OR creat* OR disseminat* OR deploy*) NEAR/2 (disinformation OR misinformation OR "fake content" OR "deep fake*" OR deepfake*))))	10,462
11 AI *only*	**TS**=("artificial intelligence" OR "AI" OR "artificial general intelligence" OR "super intelligen*" OR superintelligen* OR "machine learning" OR "machine intelligence" OR "computational intelligence" OR "deep learning" OR singularity OR GPT* OR "generative pre trained transformer*" OR "generative artificial intelligence" OR "generative AI" OR ChatGPT* OR GPT* OR "Open AI" OR OpenAI OR ((autonomous OR automated) NEAR/2 (militar* OR weapon*)) OR cyborg* OR robot* OR "bot" OR "bots" OR "auto catastroph*" OR "human artificial intelligence hybrid*" OR ((human* OR biologic*) NEAR/2 ("artificial intelligence" OR "machine intelligence")) OR (Google NEAR/1 Bard) OR "LLaMA" OR ((artificial OR computer*) NEAR/1 "neural net*"))	126,615
12 All threats	#5 OR #6 OR #7 OR #8 OR #9 OR #10	30,642
13 All threats and risk assessments	#4 AND **#12** AND (PY==("2013" OR "2014" OR "2015" OR "2016" OR "2017" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023") AND LA==("ENGLISH"))	27
14 Pandemics and bioterrorism	(#4 AND **#5**) AND (PY==("2013" OR "2014" OR "2015" OR "2016" OR "2017" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023") AND LA==("ENGLISH"))	5
15 Nuclear war	(#4 AND **#6**) AND (PY==("2013" OR "2014" OR "2015" OR "2016" OR "2017" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023") AND LA==("ENGLISH"))	6
16 Asteroids	(#4 AND **#7**) AND (PY==("2013" OR "2014" OR "2015" OR "2016" OR "2017" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023") AND LA==("ENGLISH"))	3
17 Supervolcanoes	(#4 AND **#8**) AND (PY==("2013" OR "2014" OR "2015" OR "2016" OR "2017" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023") AND LA==("ENGLISH"))	??
18 Extreme climate change	(#4 AND **#9**) AND (PY==("2013" OR "2014" OR "2015" OR "2016" OR "2017" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023") AND LA==("ENGLISH"))	4
19 AI threats	(#4 AND **#10**) AND (PY==("2013" OR "2014" OR "2015" OR "2016" OR "2017" OR "2018" OR "2019" OR "2020" OR "2021" OR "2022" OR "2023") AND LA==("ENGLISH"))	16

Table A.3—Continued

Set	Search	Number of Results
Subsets		
Catastrophic risk assessment, all threats, and AI *only*	#11 AND #13	16

TABLE A.4

Scopus Literature Search and Results

Set	Search	Number of Results
1 Risk assessment	**TITLE-ABS**((risk* OR threat*) W/3 (analy* OR assess* OR avert* OR avoid* OR detect* OR estimat* OR evaluat* OR foresight* OR framework* OR likelihood* OR manag* OR measur* OR mitigat* OR model* OR monitor* OR predict* OR prevent* OR probabilit* OR surveill* OR stochastic*))	1,096,331
2 Catastrophic or existential risks	**TITLE-ABS**((catastroph* OR existential) W/1 (risk* OR threat*))	4,303
3 Global catastrophes	**TITLE-ABS**("global catastroph*" OR GCR* OR "doomsday scenario*" OR apocalyp* OR armageddon OR omnicid* OR (existential W/1 catastroph*) OR ((human* OR planet*) W/2 (extinction* OR decimat*)) OR (world W/2 end) OR ((catastroph* OR existential OR cataclysm* OR "life ending*") W/1 threat*) OR megacatastroph* OR "mega catastroph*" OR ((mass* OR complete OR full OR total OR global OR catastroph*) W/1 (collaps* OR extinction* OR destruct* OR devastat* OR obliterat* OR annihilat* OR decimat* OR morality OR "death toll*" OR famine* OR disaster* OR eradicat*)) OR ((environmental OR ecosystem* OR "eco system*" OR social OR societ* OR humanit* OR civilis* OR civiliz* OR anthropogenic) W/1 (collaps* OR catastroph* OR cataclysm*)) OR "abrupt sunlight reduction*" OR ASRS* OR ((food* OR water* OR agricultur* OR telecommunicat* OR electric*) W/1 (system* OR supply OR chain* OR "breadbasket" OR "bread basket" OR infrastructure* OR "infra structure*" OR "industrial control*") W/2 (fail* OR collaps* OR crisis OR scarcity OR contaminat* OR disrupt*)) OR ((nuclear OR impact OR volcanic) W/1 winter) OR (CBRN* AND (catastroph* OR risk*)))	77,592
4	((#1 OR #2) AND #3) Limits: 2013-2023; English; Article, Review	2,456
5 Pandemics and bioterrorism	**TITLE-ABS**(bioterror* OR "bio terror*" OR "biological warfare*" OR biowarfare OR "bio warfare" OR (biological W/1 attack*) OR "biological weapon*" OR bioweapon* OR "bio weapon*" OR "biological agent*" OR "bio agent*" OR "global catastrophic biological risk*" OR GCBR* OR biosecurity OR "chemical weapon*" OR CBRN* OR ((synthetic OR "human manufactur*" OR "man made" OR modif* OR weaponiz* OR manipulat* OR chimer* OR engineered OR catastroph*) W/2 (virus* OR viral OR bacter* OR mycosis OR mycotic OR fungi OR fungal OR pandemic* OR pathogen* OR toxin* OR "harmful agent*" OR "lethal agent*")) OR ((severe OR extreme OR sudden OR global OR mass* OR catastroph* OR disaster*) W/2 (pandemic* OR "global public health" OR epidemic* OR outbreak* OR plague*)))	113,039
6 Nuclear war	**TITLE-ABS**(((nuclear OR thermonuclear OR "thermo nuclear" OR radioactive) W/2 (war* OR strike* OR attack* OR missile* OR weapon* OR bomb* OR destruct* OR terrori* OR explosion* OR catastroph* OR annihilat*)) OR CBRN* OR "nuclear winter*" OR "high altitude electromagnetic pulse*" OR "high altitude electro magnetic pulse*" OR (weapon* W/1 "mass destruction") OR "intercontinental ballistic missile*" OR ((nuclear OR radioactive) W/2 (fallout OR waste*)))	64,465
7 Asteroids and meteors	**TITLE-ABS**(asteroid* OR comet* OR meteor* OR bolide* OR superbolide* OR "planetary defense*" OR "planetary defence*" OR "near earth object*" OR NEO* OR ((astronomical OR interstellar OR cosmic OR extraterrestrial OR stellar) W/1 (threat* OR impact* OR collision* OR object*)) OR (("near earth" OR "potentially hazardous" OR "large crater forming" OR fireball* OR "impact event*" OR "impact risk*" OR "impact winter*" OR "earth crossing*" OR "planet destroy*" OR "planet sterili*" OR catastroph*) W/1 (asteroid* OR meteor* OR bolide* OR comet*)))	1,577,928

Table A.4—Continued

Set	Search	Number of Results
8 Supervolcanoes	**TITLE-ABS**(“super volcan*” OR “massive volcan*” OR supervolcan* OR megavolcan* OR “mega volcan*” OR “large igneous province*” OR (massive W/1 eruption*) OR (super W/1 eruption*) OR “supereruption*” OR (mega W/1 eruption*) OR (eruption* W/2 (“large magnitude” OR “magnitude 8” OR M8)) OR (“flood basalt” W/2 (erupt* OR event*)) OR ((flood OR massive OR super OR mega OR floor) W/2 (“lava erupt*” OR “lava event*”)) OR “volcanic winter*” OR (volcan* W/2 (“oceanic anoxic event*” OR euxin* OR catastroph*)))	4,316
9 Extreme climate change	**TITLE-ABS**(((severe OR extreme OR sudden OR abrupt* OR global OR mass* OR catastroph* OR disaster* OR runaway) W/1 (“climate change*” OR “global warming” OR “natural disaster*”)) OR ((climat* OR ecosystem* OR “eco system*”) W/1 (catastroph* OR disaster* OR collaps*)) OR (environment* W/1 devastation) OR “extreme temperature change*” OR (disruption* W/2 (“global oceanic” OR “global atmospheric current*”)) OR (climate W/2 (“global oceanic” OR “global atmospher* current*”)) OR ((evaporat* OR melt* OR collapse*) W/1 (“global ocean*” OR “sea ice” OR glacier* OR “ice cap*” OR “ice sheet*”)) OR “melt* water” OR meltwater OR (“extreme weather” W/2 (acidif* OR deoxygen*)) OR (“global ocean*” W/1 (anox* OR euxin*)) OR (ocean* W/1 (“temperature change*” OR warming)) OR ((rapid OR extreme) W/1 rise* W/1 (“sea level*” OR “ocean level*”)))	163,040
10 AI threats	**TITLE-ABS**((“artificial intelligence” OR “AI” OR “artificial general intelligence” OR “super intelligen*” OR superintelligen* OR “machine learning” OR “machine intelligence” OR “computational intelligence” OR “deep learning” OR singularity OR GPT* OR “generative pre trained transformer*” OR “generative artificial intelligence” OR “generative AI” OR ChatGPT* OR GPT* OR “Open AI” OR OpenAI OR ((autonomous OR automated) W/2 (militar* OR weapon*)) OR cyborg* OR robot* OR “bot” OR “bots” OR “auto catastroph*” OR “human artificial intelligence hybrid*” OR ((human* OR biologic*) W/2 (“artificial intelligence” OR “machine intelligence”)) OR (Google W/1 Bard) OR “LLaMA” OR ((artificial OR computer*) W/1 “neural net*”)) AND (terror* OR “take over*” OR takeover* OR provok* OR weapon* OR hack* OR catastrop* OR apocalyp* OR threat* OR attack* OR harm* OR adversar* OR offens* OR disrupt* OR ((data OR information) W/2 (poison* OR corrupt* OR manipulat*)) OR “decisive strategic advantage” OR “instrumental convergence” OR “intelligence explosion*” OR “AI safety” OR “AI security” OR ((generat* OR creat* OR disseminat* OR deploy*) W/2 (disinformation OR misinformation OR “fake content” OR “deep fake*” OR deepfake*))))	93,234
11 AI *only*	**TITLE-ABS**(“artificial intelligence” OR “AI” OR “artificial general intelligence” OR “super intelligen*” OR superintelligen* OR “machine learning” OR “machine intelligence” OR “computational intelligence” OR “deep learning” OR singularity OR GPT* OR “generative pre trained transformer*” OR “generative artificial intelligence” OR “generative AI” OR ChatGPT* OR GPT* OR “Open AI” OR OpenAI OR ((autonomous OR automated) W/2 (militar* OR weapon*)) OR cyborg* OR robot* OR “bot” OR “bots” OR “auto catastroph*” OR “human artificial intelligence hybrid*” OR ((human* OR biologic*) W/2 (“artificial intelligence” OR “machine intelligence”)) OR (Google W/1 Bard) OR “LLaMA” OR ((artificial OR computer*) W/1 “neural net*”))	1,551,655
12 All threats	#5 OR #6 OR #7 OR #8 OR #9 OR #10	1,998,794
13 All threats and risk assessments	#4 AND **#12**	464
14 Pandemics and bioterrorism	#4 AND **#5**	99
15 Nuclear war	#4 AND **#6**	112
16 Asteroids	#4 AND **#7**	88
17 Supervolcanoes	#4 AND **#8**	10
18 Extreme climate change	#4 AND **#9**	195
19 AI threats	#4 AND **#10**	63

Table A.4—Continued

Set	Search	Number of Results
Subsets		
Catastrophic risk assessment, all threats, and AI *only*	#11 AND #13	67
Catastrophic risk assessment, pandemics, and AI *only*	#11 AND #14	7
Nuclear war and AI *only*	#11 AND #15	8

TABLE A.5

Academic Search Complete Literature Search and Results

Set	Search	Number of Results
1 Risk assessment	TI((risk* OR threat*) N3 (analy* OR assess* OR avert* OR avoid* OR detect* OR estimat* OR evaluat* OR foresight* OR framework* OR likelihood* OR manag* OR measur* OR mitigat* OR model* OR monitor* OR predict* OR prevent* OR probabilit* OR surveill* OR stochastic*)) OR AB((risk* OR threat*) N3 (analy* OR assess* OR avert* OR avoid* OR detect* OR estimat* OR evaluat* OR foresight* OR framework* OR likelihood* OR manag* OR measur* OR mitigat* OR model* OR monitor* OR predict* OR prevent* OR probabilit* OR surveill* OR stochastic*))	422,232
2 Catastrophic or existential risks	TI((catastroph* OR existential) N1 (risk* OR threat*)) OR AB((catastroph* OR existential) N1 (risk* OR threat*))	2,045
3 Global catastrophes	TI("global catastroph*" OR GCR* OR "doomsday scenario*" OR apocalyp* OR armageddon OR omnicid* OR (existential N1 catastroph*) OR ((human* OR planet*) N2 (extinction* OR decimat*)) OR (world N2 end) OR ((catastroph* OR existential OR cataclysm* OR "life ending*") N1 threat*) OR (extinction N1 risk*) OR megacatastroph* OR "mega catastroph*" OR ((mass* OR complete OR full OR total OR global OR catastroph*) N1 (collaps* OR extinction* OR destruct* OR devastat* OR obliterat* OR annihilat* OR decimat* OR morality OR "death toll*" OR famine* OR disaster* OR eradicat*)) OR ((environmental OR ecosystem* OR "eco system*" OR social OR societ* OR humanit* OR civilis* OR civiliz* OR anthropogenic) N1 (collaps* OR catastroph* OR cataclysm*)) OR "abrupt sunlight reduction*" OR ASRS* OR ((food* OR water* OR agricultur* OR telecommunicat* OR electric*) N1 (system* OR supply OR chain* OR "breadbasket" OR "bread basket" OR infrastructure* OR "infra structure*" OR "industrial control*") N2 (fail* OR collaps* OR crisis OR scarcity OR contaminat* OR disrupt*)) OR ((nuclear OR impact OR volcanic) N1 winter) OR (CBRN* AND (catastroph* OR risk*))) OR AB("global catastroph*" OR GCR* OR "doomsday scenario*" OR apocalyp* OR armageddon OR omnicid* OR (existential N1 catastroph*) OR ((human* OR planet*) N2 (extinction* OR decimat*)) OR (world N2 end) OR ((catastroph* OR existential OR cataclysm* OR "life ending*") N1 threat*) OR (extinction N1 risk*) OR megacatastroph* OR "mega catastroph*" OR ((mass* OR complete OR full OR total OR global OR catastroph*) N1 (collaps* OR extinction* OR destruct* OR devastat* OR obliterat* OR annihilat* OR decimat* OR morality OR "death toll*" OR famine* OR disaster* OR eradicat*)) OR ((environmental OR ecosystem* OR "eco system*" OR social OR societ* OR humanit* OR civilis* OR civiliz* OR anthropogenic) N1 (collaps* OR catastroph* OR cataclysm*)) OR "abrupt sunlight reduction*" OR ASRS* OR ((food* OR water* OR agricultur* OR telecommunicat* OR electric*) N1 (system* OR supply OR chain* OR "breadbasket" OR "bread basket" OR infrastructure* OR "infra structure*" OR "industrial control*") N2 (fail* OR collaps* OR crisis OR scarcity OR contaminat* OR disrupt*)) OR ((nuclear OR impact OR volcanic) N1 winter) OR (CBRN* AND (catastroph* OR risk*)))	51,624
4	((S1 OR S2) AND S3) Limits: 2013-2023; English; Academic Journals	2,034

Table A.5—Continued

Set	Search	Number of Results
5 Pandemics and bioterrorism	TI(bioterror* OR "bio terror*" OR "biological warfare*" OR biowarfare OR "bio warfare" OR (biological N1 attack*) OR "biological weapon*" OR bioweapon* OR "bio weapon*" OR "biological agent*" OR "bio agent*" OR "global catastrophic biological risk*" OR GCBR* OR biosecurity OR "chemical weapon*" OR CBRN* OR ((synthetic OR "human manufactur*" OR "man made" OR modif* OR weaponiz* OR manipulat* OR chimer* OR engineered OR catastroph*) N2 (virus* OR viral OR bacter* OR mycosis OR mycotic OR fungi OR fungal OR pandemic* OR pathogen* OR toxin* OR "harmful agent*" OR "lethal agent*")) OR ((severe OR extreme OR sudden OR global OR mass* OR catastroph* OR disaster*) N2 (pandemic* OR "global public health" OR epidemic* OR outbreak* OR plague*))) OR AB(bioterror* OR "bio terror*" OR "biological warfare*" OR biowarfare OR "bio warfare" OR (biological N1 attack*) OR "biological weapon*" OR bioweapon* OR "bio weapon*" OR "biological agent*" OR "bio agent*" OR "global catastrophic biological risk*" OR GCBR* OR biosecurity OR "chemical weapon*" OR CBRN* OR ((synthetic OR "human manufactur*" OR "man made" OR modif* OR weaponiz* OR manipulat* OR chimer* OR engineered OR catastroph*) N2 (virus* OR viral OR bacter* OR mycosis OR mycotic OR fungi OR fungal OR pandemic* OR pathogen* OR toxin* OR "harmful agent*" OR "lethal agent*")) OR ((severe OR extreme OR sudden OR global OR mass* OR catastroph* OR disaster*) N2 (pandemic* OR "global public health" OR epidemic* OR outbreak* OR plague*)))	36,539
6 Nuclear war	TI(((nuclear OR thermonuclear OR "thermo nuclear" OR radioactive) N2 (war* OR strike* OR attack* OR missile* OR weapon* OR bomb* OR destruct* OR terrori* OR explosion* OR catastroph* OR annihilat*)) OR CBRN* OR "nuclear winter*" OR "high altitude electromagnetic pulse*" OR "high altitude electro magnetic pulse*" OR (weapon* N1 "mass destruction") OR "intercontinental ballistic missile*" OR ((nuclear OR radioactive) N2 (fallout OR waste*))) OR AB(((nuclear OR thermonuclear OR "thermo nuclear" OR radioactive) N2 (war* OR strike* OR attack* OR missile* OR weapon* OR bomb* OR destruct* OR terrori* OR explosion* OR catastroph* OR annihilat*)) OR CBRN* OR "nuclear winter*" OR "high altitude electromagnetic pulse*" OR "high altitude electro magnetic pulse*" OR (weapon* N1 "mass destruction") OR "intercontinental ballistic missile*" OR ((nuclear OR radioactive) N2 (fallout OR waste*)))	15,757
7 Asteroids and meteors	TI(asteroid* OR comet* OR meteor* OR bolide* OR superbolide* OR "planetary defense*" OR "planetary defence*" OR "near earth object*" OR NEO* OR ((astronomical OR interstellar OR cosmic OR extraterrestrial OR stellar) N1 (threat* OR impact* OR collision* OR object*)) OR (("near earth" OR "potentially hazardous" OR "large crater forming" OR fireball* OR "impact event*" OR "impact risk*" OR "impact winter*" OR "earth crossing*" OR "planet destroy*" OR "planet sterili*" OR catastroph*) N1 (asteroid* OR meteor* OR bolide* OR comet*))) OR AB(asteroid* OR comet* OR meteor* OR bolide* OR superbolide* OR "planetary defense*" OR "planetary defence*" OR "near earth object*" OR NEO* OR ((astronomical OR interstellar OR cosmic OR extraterrestrial OR stellar) N1 (threat* OR impact* OR collision* OR object*)) OR (("near earth" OR "potentially hazardous" OR "large crater forming" OR fireball* OR "impact event*" OR "impact risk*" OR "impact winter*" OR "earth crossing*" OR "planet destroy*" OR "planet sterili*" OR catastroph*) N1 (asteroid* OR meteor* OR bolide* OR comet*)))	343,894
8 Supervolcanoes	TI("super volcan*" OR "massive volcan*" OR supervolcan* OR megavolcan* OR "mega volcan*" OR "large igneous province*" OR (massive N1 eruption*) OR (super N1 eruption*) OR "supereruption*" OR (mega N1 eruption*) OR (eruption* N2 ("large magnitude" OR "magnitude 8" OR M8)) OR ("flood basalt" N2 (erupt* OR event*)) OR ((flood OR massive OR super OR mega OR floor) N2 ("lava erupt*" OR "lava event*")) OR "volcanic winter*" OR (volcan* N2 ("oceanic anoxic event*" OR euxin* OR catastroph*))) OR AB("super volcan*" OR "massive volcan*" OR supervolcan* OR megavolcan* OR "mega volcan*" OR "large igneous province*" OR (massive N1 eruption*) OR (super N1 eruption*) OR "supereruption*" OR (mega N1 eruption*) OR (eruption* N2 ("large magnitude" OR "magnitude 8" OR M8)) OR ("flood basalt" N2 (erupt* OR event*)) OR ((flood OR massive OR super OR mega OR floor) N2 ("lava erupt*" OR "lava event*")) OR "volcanic winter*" OR (volcan* N2 ("oceanic anoxic event*" OR euxin* OR catastroph*)))	1,964

Table A.5—Continued

Set	Search	Number of Results
9 Extreme climate change	TI(((severe OR extreme OR sudden OR abrupt* OR global OR mass* OR catastroph* OR disaster* OR runaway) N1 (“climate change*” OR “global warming” OR “natural disaster*”)) OR ((climat* OR ecosystem* OR “eco system*”) N1 (catastroph* OR disaster* OR collaps*)) OR (environment* N1 devastation) OR “extreme temperature change*” OR (disruption* N2 (“global oceanic” OR “global atmospheric current*”)) OR (climate N2 (“global oceanic” OR “global atmospher* current*”)) OR ((evaporat* OR melt* OR collapse*) N1 (“global ocean*” OR “sea ice” OR glacier* OR “ice cap*” OR “ice sheet*”)) OR “melt* water” OR meltwater OR (“extreme weather” N2 (acidif* OR deoxygen*)) OR (“global ocean*” N1 (anox* OR euxin*)) OR (ocean* N1 (“temperature change*” OR warming)) OR ((rapid OR extreme) N1 rise* N1 (“sea level*” OR “ocean level*”))) OR AB(((severe OR extreme OR sudden OR abrupt* OR global OR mass* OR catastroph* OR disaster* OR runaway) N1 (“climate change*” OR “global warming” OR “natural disaster*”)) OR ((climat* OR ecosystem* OR “eco system*”) N1 (catastroph* OR disaster* OR collaps*)) OR (environment* N1 devastation) OR “extreme temperature change*” OR (disruption* N2 (“global oceanic” OR “global atmospheric current*”)) OR (climate N2 (“global oceanic” OR “global atmospher* current*”)) OR ((evaporat* OR melt* OR collapse*) N1 (“global ocean*” OR “sea ice” OR glacier* OR “ice cap*” OR “ice sheet*”)) OR “melt* water” OR meltwater OR (“extreme weather” N2 (acidif* OR deoxygen*)) OR (“global ocean*” N1 (anox* OR euxin*)) OR (ocean* N1 (“temperature change*” OR warming)) OR ((rapid OR extreme) N1 rise* N1 (“sea level*” OR “ocean level*”)))	50,337
10 AI threats	TI((“artificial intelligence” OR “AI” OR “artificial general intelligence” OR “super intelligen*” OR superintelligen* OR “machine learning” OR “machine intelligence” OR “computational intelligence” OR “deep learning” OR singularity OR GPT* OR “generative pre trained transformer*” OR “generative artificial intelligence” OR “generative AI” OR ChatGPT* OR GPT* OR “Open AI” OR OpenAI OR ((autonomous OR automated) N2 (militar* OR weapon*)) OR cyborg* OR robot* OR “bot” OR “bots” OR “auto catastroph*” OR “human artificial intelligence hybrid*” OR ((human* OR biologic*) N2 (“artificial intelligence” OR “machine intelligence”)) OR (Google N1 Bard) OR “LLaMA” OR ((artificial OR computer*) N1 “neural net*”)) AND (terror* OR “take over*” OR takeover* OR provok* OR weapon* OR hack* OR catastrop* OR apocalyp* OR threat* OR attack* OR harm* OR adversar* OR offens* OR disrupt* OR ((data OR information) N2 (poison* OR corrupt* OR manipulat*)) OR “decisive strategic advantage” OR “instrumental convergence” OR “intelligence explosion*” OR “AI safety” OR “AI security” OR ((generat* OR creat* OR disseminat* OR deploy*) N2 (disinformation OR misinformation OR “fake content” OR “deep fake*” OR deepfake*)))) OR AB((“artificial intelligence” OR “AI” OR “artificial general intelligence” OR “super intelligen*” OR superintelligen* OR “machine learning” OR “machine intelligence” OR “computational intelligence” OR “deep learning” OR singularity OR GPT* OR “generative pre trained transformer*” OR “generative artificial intelligence” OR “generative AI” OR ChatGPT* OR GPT* OR “Open AI” OR OpenAI OR ((autonomous OR automated) N2 (militar* OR weapon*)) OR cyborg* OR robot* OR “bot” OR “bots” OR “auto catastroph*” OR “human artificial intelligence hybrid*” OR ((human* OR biologic*) N2 (“artificial intelligence” OR “machine intelligence”)) OR (Google N1 Bard) OR “LLaMA” OR ((artificial OR computer*) N1 “neural net*”)) AND (terror* OR “take over*” OR takeover* OR provok* OR weapon* OR hack* OR catastrop* OR apocalyp* OR threat* OR attack* OR harm* OR adversar* OR offens* OR disrupt* OR ((data OR information) N2 (poison* OR corrupt* OR manipulat*)) OR “decisive strategic advantage” OR “instrumental convergence” OR “intelligence explosion*” OR “AI safety” OR “AI security” OR ((generat* OR creat* OR disseminat* OR deploy*) N2 (disinformation OR misinformation OR “fake content” OR “deep fake*” OR deepfake*))))	16,799

Table A.5—Continued

Set	Search	Number of Results
11 AI *only*	TI("artificial intelligence" OR "AI" OR "artificial general intelligence" OR "super intelligen*" OR superintelligen* OR "machine learning" OR "machine intelligence" OR "computational intelligence" OR "deep learning" OR singularity OR GPT* OR "generative pre trained transformer*" OR "generative artificial intelligence" OR "generative AI" OR ChatGPT* OR GPT* OR "Open AI" OR OpenAI OR ((autonomous OR automated) N2 (militar* OR weapon*)) OR cyborg* OR robot* OR "bot" OR "bots" OR "auto catastroph*" OR "human artificial intelligence hybrid*" OR ((human* OR biologic*) N2 ("artificial intelligence" OR "machine intelligence")) OR (Google N1 Bard) OR "LLaMA" OR ((artificial OR computer*) N1 "neural net*")) OR AB("artificial intelligence" OR "AI" OR "artificial general intelligence" OR "super intelligen*" OR superintelligen* OR "machine learning" OR "machine intelligence" OR "computational intelligence" OR "deep learning" OR singularity OR GPT* OR "generative pre trained transformer*" OR "generative artificial intelligence" OR "generative AI" OR ChatGPT* OR GPT* OR "Open AI" OR OpenAI OR ((autonomous OR automated) N2 (militar* OR weapon*)) OR cyborg* OR robot* OR "bot" OR "bots" OR "auto catastroph*" OR "human artificial intelligence hybrid*" OR ((human* OR biologic*) N2 ("artificial intelligence" OR "machine intelligence")) OR (Google N1 Bard) OR "LLaMA" OR ((artificial OR computer*) N1 "neural net*"))	302,593
12 All threats	S5 OR S6 OR S7 OR S8 OR S9 OR S10	460,241
13 All threats and risk assessments	S4 AND S12	309
14 Pandemics and bioterrorism	S4 AND S5	29
15 Nuclear war	S4 AND S6	30
16 Asteroids	S4 AND S7	9
17 Supervolcanoes	S4 AND S8	2
18 Climate change	S4 AND S9	21
19 AI threats	S4 AND S10	21
Subsets		
Catastrophic risk assessment, all threats, and AI *only*	S11 AND S13	92
Catastrophic risk assessment, pandemics, and AI *only*	S11 AND S14	6
Nuclear war and AI *only*	S11 AND S15	10

Glossary

In this appendix, we provide additional information about terms that might be unfamiliar to the lay reader.

albedo. Albedo is

> the fraction of light that a surface reflects. If it is all reflected, the albedo is equal to 1. If 30% is reflected, the albedo is 0.3. The albedo of Earth's surface (atmosphere, ocean, land surfaces) determines how much incoming solar energy, or light, is immediately reflected back to space. This can have an impact on climate.[1]

alignment problem. "[T]he alignment problem is simply the issue of how to make sure that the goals of an AI system are aligned with those of humanity."[2]

blackbody. A blackbody is "an ideal body or surface that completely absorbs all radiant energy falling upon it with no reflection and that radiates at all frequencies with a spectral energy distribution dependent on its absolute temperature."[3]

Earth-system approach. An Earth-system approach is one that views Earth as consisting of a system of systems, with those component systems being defined differently by different research groups but essentially being air, water, ice, earth, and organisms.[4]

experts, superforecasters. Experts are "specialists on long-run existential risks to humanity," and superforecasters are "[h]istorically accurate forecasters [with] a proven track record at forecasting resolvable questions over short time horizons."[5]

greenhouse agent. Greenhouse agents are high-potency greenhouse gases, such as fluorinated gas, meant to counteract the cooling from volcanic aerosols. They have long life spans in the atmosphere and are more potent than carbon dioxide.

ignimbrite. An ignimbrite is a heat-welded deposit into a solid rock from an ash flow.[6]

lofting. The sun's energy in the atmosphere can cause dark aerosols to absorb energy. With more energy, these aerosols would be warmer and, if gases, less dense. Warmer and less dense things rise. Thus, they would be lofted into the higher layers of Earth's atmosphere. Once there, they could block the sun and possibly stay there for a long time doing so.

meteor, meteorite. When smaller objects, those a few meters or less in diameter, collide with Earth, they burn up harmlessly high in the atmosphere, creating a streak of light (called a *meteor*) that often—especially

[1] My NASA Data, "What Is Albedo?"

[2] Existential Risk Observatory, "Unaligned AI."

[3] "Blackbody."

[4] See, for example, My NASA Data, "About the Earth as a System."

[5] Karger et al., Forecasting Existential Risks, p. 3.

[6] Aniakchak National Monument and Preserve et al., "Pyroclastic Flows and Ignimbrites, and Pyroclastic Surges."

at night—can be seen from the ground. The meteoroid is the object; if it reaches the surface, it is called a *meteorite*.[7]

millirem. A roentgen-equivalent man (rem) is a unit of effective radiation dose used to estimate the possible health effects of ionizing radiation. It is defined as the absorbed radiation dose, in rads, multiplied by a relative biological effectiveness factor.)

misinformation, disinformation, malinformation. The Cybersecurity and Infrastructure Security Agency defines misinformation, disinformation, and malinformation as follows:

> Misinformation is false, but not created or shared with the intention of causing harm. Disinformation is deliberately created to mislead, harm, or manipulate a person, social group, organization, or country. Malinformation is based on fact, but used out of context to mislead, harm, or manipulate.[8]

ring vaccination. Ring vaccination is a public health approach in which people in contact with confirmed patients are vaccinated, as are people who are in close contact with those contacts.[9]

sky bot. A sky bot is a concept drone or aerial robot that would fly into the supervolcano eruption and suck up both ash and sulfur dioxide.

solar irradiance. Solar irradiance is "the output of light energy from the sun that reaches the earth. It is measured in terms of the amount of sunlight that hits a square meter of a surface in one second."[10]

tephra. Tephra is "all pieces of all fragments of rock ejected into the air by an erupting volcano."[11]

thermal expansion. Thermal expansion is the physical process by which water expands as it warms and thus occupies greater space. This translates into sea-level rise.

tuff. Tuff is "consolidated (hardened and/or compacted) pyroclastic (explosive, volcanic origination) rocks."[12]

volcanic explosivity index. The volcanic explosivity index (VEI) is a logarithmic scale of eruption size created by Newhall and Self based on a combination of erupted volume and eruption plume height.[13] Because the density of emplaced eruptive product varies widely and plume information is not available for most historical eruptions, the volcanic magnitude (M) scale was created as a proxy for the VEI.[14] M considers the mass of erupted material (computed from the volume and density) and is expressed as $\log_{10}$(erupted mass in kilograms) – 7.[15] M values approximate VEI values and are more comparable than VEI values between multiple eruptions. The VEI scale goes from 0 to 8. *VEI 8* describes a very large eruption with at least 10^{12} m^3 of a violently ejected, narrow stream of gas and ash in a column at least 25 km high that can be described as "cataclysmic, paroxysmal, colossal" or "severe, violent, terrific." Its blast can last more than 12 hours and inject substantial amounts of material into the troposphere and significant amounts into the stratosphere.[16]

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7 See NASA Space Place, "Asteroid or Meteor?"

8 Cybersecurity and Infrastructure Security Agency, "Foreign Influence Operations and Disinformation."

9 See Centers for Disease Control and Prevention, "Ring Vaccination."

10 Opie, "The Importance of Solar Irradiance and Meteorological Data for PV Design."

11 Cascades Volcano Observatory, "Tephra Fall Is a Widespread Volcanic Hazard."

12 Volcano Hazards Program, "Tuff."

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14 Pyle, "Sizes of Volcano Eruptions."

15 Pyle, "Sizes of Volcano Eruptions."

16 See Yellowstone Volcano Observatory, "The Volcanic Explosivity Index."

APPENDIX C

Works Cited, by Chapter

In this appendix, we list all the works cited in this report, organized by chapter.

About This Report

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Chapter 10

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Abbreviations

AGI	artificial general intelligence
AI	artificial intelligence
BC	black carbon
BW	biological weapon
BWC	Biological Weapons Convention
CO_2	carbon dioxide
COVID-19	coronavirus disease 2019
DAI	dangerous anthropogenic interference
DAN	do anything now
DART	double asteroid redirection test
DHS	U.S. Department of Homeland Security
DNA	deoxyribonucleic acid
DNN	deep neural network
DoD	U.S. Department of Defense
EID	emerging infectious disease
EMP	electromagnetic pulse
ENSO	El Niño–Southern Oscillation
ESA	European Space Agency
FEMA	Federal Emergency Management Agency
GCRMA	Global Catastrophic Risk Management Act
GDP	gross domestic product
GHG	greenhouse gas
HTHH	Hunga Tonga–Hunga Ha'apai
ICBM	intercontinental ballistic missile
IPCC	Intergovernmental Panel on Climate Change
IRGC	International Risk Governance Council
JPL	Jet Propulsion Laboratory
LLM	large language model
M	volcanic magnitude
MCM	medical countermeasure
MERS	Middle East respiratory syndrome
Mt	megaton
NASA	National Aeronautics and Space Administration
NCA5	Fifth National Climate Assessment
NEO	near-Earth object
NIST	National Institute of Standards and Technology
OECD	Organisation for Economic Co-operation and Development

PDCO	Planetary Defense Coordination Office
P&R	preparedness and response
R0	replication rate
RNA	ribonucleic acid
SARS	severe acute respiratory syndrome
SARS-CoV-2	severe acute respiratory syndrome coronavirus 2
SCADA	supervisory control and data acquisition
SQL	structured query language
ssRNA	single-stranded ribonucleic acid
Tg	teragram
TNT	trinitrotoluene
TTX	tabletop exercise
UNFCCC	United Nations Framework Convention on Climate Change
USGS	U.S. Geological Survey
UV	ultraviolet
VEI	volcanic explosivity index
WHO	World Health Organization

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Global catastrophic and existential risks hold the potential to threaten human civilization. Addressing these risks is crucial for ensuring humans' long-term survival and flourishing. Motivated by the gravity of these risks, Congress passed the Global Catastrophic Risk Management Act in 2022, which requires that the Secretary of Homeland Security and the administrator of the Federal Emergency Management Agency coordinate an assessment of global catastrophic risk related to a set of threats and hazards. The U.S. Department of Homeland Security Science and Technology Directorate and the Federal Emergency Management Agency requested the Homeland Security Operational Analysis Center's support in meeting this requirement. The authors of this report document findings from the resulting analysis.

This report summarizes what is known about the risks associated with six threats and hazards: artificial intelligence; asteroid and comet impacts; sudden and severe changes to Earth's climate; nuclear war; severe pandemics, whether resulting from naturally occurring events or from synthetic biology; and supervolcanoes.

The risk summaries cover the following aspects: where feasible, estimates of the likelihood and potential consequences of each risk; factors causing the risk and associated uncertainties; and whether the risk is likely to change in the next decade.

Because the broader goal of the Global Catastrophic Risk Management Act is to reduce risk to human civilization, the authors also identified known and potential mitigation strategies for the six threats and hazards and drew insights from the assessment relevant to managing the risks they pose to society.

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