Climate Endgame: antologia di scritti

A CURA DI MICHELE CARDUCCI

Working Paper del Laboratorio di analisi ecologica del diritto
QUADERNO N. 3

INDICE DELL'ANTOLOGIA

World Scientists' Warning of a Climate Emergency 2022

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We are now at "code red" on planet Earth. Humanity is unequivocally facing a climate emergency. The scale of untold human suffering, already immense, is rapidly growing with the escalating number of climate-related disasters. Therefore, we urge scientists, citizens, and world leaders to read this Special Report and quickly take the necessary actions to avoid the worst effects of climate change.

2022 marks the 30th anniversary of the "World Scientists' Warning to Humanity," signed by more than 1700 scientists in 1992. Since this original warning, there has been a roughly 40% increase in global greenhouse gas emissions. This is despite numerous written warnings from the Intergovernmental Panel on Climate Change and a recent scientists' warning of a climate emergency with nearly 15,000 signatories from 158 countries (Ripple et al. 2020). Current policies are taking the planet to around 3 degrees Celsius warming by 2100, a temperature level that Earth has not experienced over the past 3 million years (Liu and Raftery 2021). The consequences of global heating are becoming increasingly extreme, and outcomes such as global societal collapse are plausible and dangerously underexplored (Kemp et al. 2022). Motivated by the moral urgency of this global crisis, here, we track recent climate-related disasters, assess planetary vital signs, and provide sweeping policy recommendations.

Climate-related extreme weather

Climate change has increased the frequency and intensity of severe weather events across the world (Coronese et al. 2019). This is likely because of a variety of interconnected processes, including an overall warming trend, changing precipitation patterns, rising sea levels, and changes in the jet streams. For example, rapid Arctic warming may have made the summer jet stream in the Northern Hemisphere more prone to meandering and becoming blocked, causing heat waves, flooding, droughts, and other disasters (Mann et al. 2017). Rather than just being more frequent, some extreme weather events are now more intense or sometimes occur closer together in time and space. This compounds damage and decreases recovery time. It may increase the likelihood of extreme risks such as simultaneous global failure of crop yields across multiple major food producing regions.

We are now regularly seeing events and disasters that previously occurred only rarely. Tragically, these disasters disproportionately harm poor people in low-income regions that have had minimal contributions to the buildup of greenhouse gasses. For example, in the summer of 2022, one third of Pakistan was flooded, displacing 33 million people and affecting 16 million children. Other disasters this year include terrifying wildfires in Europe, back-to-back cyclones and subsequent flooding in eastern Australia, numerous rivers drying up in China and Europe, an extraordinarily intense hurricane striking the Southeastern United States, powerful storms and extensive flooding in Bangladesh and India, megafires and a continuation of the decadal drought in the western United States, a massive flood that closed Yellowstone National Park, and unusually severe heat waves or "heat domes" in many parts of the Northern Hemisphere (see table 1 for details and attribution). These serial and simultaneous impacts are testing society's limits as they greatly reduce resilience and ability to cope with other crises. To illustrate these impacts, we provide a photo series, documenting the human cost of climate-related disasters (figure 1, supplemental file S1).

Recent trends in planetary vital signs

Updating the planetary vital signs first published by Ripple and colleagues (2020) provides a simple but powerful way to track changes in potential climate drivers (figure 2) and

BioScience XX: 1–7.
https://doi.org/10.1093/biosci/biac083

impacts (figure 3). In total, 16 of the 35 variables that we track are at record extremes based on the time series data (supplemental table S1). We discuss some of these vital signs below.

Economics. Encouragingly, there was a strong increase in global fossil fuel divestment in 2022 (figure 2j). Despite an overall decreasing trend, direct fossil fuel subsidies increased to US$440 billion in 2021, which is a worrisome rise from levels below US$200 billion (figure 2o). The percentage of greenhouse gas emissions covered by carbon pricing was relatively flat between 2021 and 2022 (figure 2m), as was the global emissions-weighted average price per tonne of carbon dioxide (approximately US$14.20 as of 2022; figure 2n). Both the proportion of emissions covered and the price of carbon need to increase dramatically to be effective in curbing global fossil fuel use (Cramton et al. 2017).

Energy. Because of the COVID-19 pandemic, global fossil fuel energy consumption decreased in 2020, along with carbon dioxide emissions and per capita carbon dioxide emissions (figure 2h, 2k, 2l). However, these declines were short-lived, and in 2021, all of these variables rose significantly again. Although solar and wind power consumption increased by roughly 18% between 2020 and 2021, it is still approximately 18 times lower than fossil fuel consumption (figure 2h). Despite the urgent need to immediately cease new fossil fuel development and reduce emissions, fossil fuel projects continue to be pursued on an enormous scale. There are currently 425 “carbon bombs”—existing or planned fossil fuel extraction projects with at least 1 gigaton of potential carbon dioxide emissions—and their potential emissions is roughly twice the 1.5-degree Celsius carbon budget (Kühne et al. 2022).

Global mean greenhouse gases and temperature. Three major greenhouse gases—carbon dioxide, methane, and nitrous oxide—all set new year-to-date records for atmospheric concentrations in 2022 (figure 3a–3c). In March of 2022, carbon dioxide concentration reached 418 parts per million, the highest monthly global average concentration ever recorded. In addition, 2022 is on track to be one of the hottest years on record (figure 3d). Ocean heat content rose greatly in 2021 and is now at a record high (figure 3i).

Climate impacts. Disasters associated at least partially to climate change have been steeply trending upward. Climate change has been linked to increases in both the frequency and intensity of extreme heat events. The number of extremely hot days has nearly doubled since 1980 (figure 3o). Globally, roughly 500,000 deaths between 2000 and 2019 were heat related, and the heat-related excess death ratio rose significantly from 2000–2003 to 2016–2019 (Zhao et al. 2021).

The impacts may not track linearly with global heating. As our global temperatures creep up, the frequency or magnitude of some types of climate disasters may actually leap up (Calvin 2019, Fischer et al. 2021). Our preliminary models indicate that this leaping pattern or threshold response may be the case in the United States for both the area burned by wildfires and the number of inland floods that have caused at least US$1 billion dollars in damages (see supplemental file S1, figures 3l, 3n, supplemental figures S2–S3). In addition, global wildfire activity appears to be exhibiting a rapid increase since 2009 (figure 3m). Because of rising temperatures and other factors such as severe windstorms, the propensity of certain mosquito species to transmit the dengue virus has risen substantially since 1980 (figure 3p). Rising temperatures increase the risks of feedback loops and tipping points being triggered, potentially including, for example, permafrost thawing and Amazon forest dieback (see supplemental file S1). Higher temperatures will increase the risk of cascading effects such as disease and conflict, as well as heighten the probability of and our vulnerability to other catastrophic threats (Kemp et al. 2022).

Climate policy

Most planetary boundaries that regulate the state of the Earth are beyond their safe space (Rockström et al. 2009; see the supplemental material). Therefore, climate change is not a stand-alone issue. It is part of a larger systemic problem of ecological overshoot where human demand is exceeding the regenerative capacity of the biosphere (Wackernagel et al. 2002). Humanity cannot sustain unlimited growth in a finite world. We need to address ecological overshoot, while at the same time ramping up climate action. Therefore, we continue our call for holistic and transformative change (e.g., Rees 2019, Ripple et al. 2020). Keys to curbing the ecological overshoot involve greatly reducing overconsumption and waste by the global middle class and especially the wealthy, stabilizing and gradually reducing the human population by providing education and rights for girls and women, and implementing a sustainable ecological economics that ensures social justice (Rees 2019).

The increasing frequency and intensity of climate disasters emphasizes the need for immediate mitigation and adaptation. In addition to protecting nature, including forests, and eliminating nearly all fossil fuel emissions, efforts should be made to explore the potential of effective carbon dioxide removal strategies, which can help cool the planet in the long term by countering historical emissions (supplemental figure S4). A sufficiently high carbon price can reduce emissions in certain sectors and encourage carbon dioxide removal. If designed well, it can also provide funding to support socially just climate adaptations and compensate for climate-related losses and damages, especially in the developing world. To further promote climate justice, this could be accomplished by returning some or all of the carbon price revenue directly to the people,

Figure 1. The impacts of climate-related droughts (left column) and floods (right column). Left column (top to bottom): "Children in dust storm" (Ethiopia, 2016; photograph: Anouk Delafortrie/EU/ECHO), a water hole that may have become empty because of drought (Mozambique, 2016; photograph: Aurélie Marrier d'Unienville/IFRC), drought-affected corn field in Paulding County, Ohio (United States, 2012; photograph: US Department of Agriculture/ Christina Reed), "Drought in Kenya's Ewaso Ngiro river basin" (Kenya, 2017; photograph: Denis Onyodi/Denis Onyodi/KRCS). Right column (top to bottom): houses are nearly submerged by flooding (Bangladesh, 2020; photograph: Moniruzzaman Sazal/Climate Visuals Countdown), "A girl, duck in hand wades through the water in Rwangara" (Uganda, 2020; photograph: Climate Centre), "two children a boy and a girl on a flooded riverbank" (Bangladesh, 2018; photograph: Moniruzzaman Sazal/Climate Visuals Countdown), "Residents wade through flooded streets to escape flood waters" (United Kingdom, 2008; John Dal). All photos are licensed under Creative Commons and all quotes are from the Climate Visuals project (https://climatevisuals.org). See supplemental file S1 for details and more pictures.

especially in low-income areas that are most vulnerable to climate impacts. More generally, other policy instruments could include investments in innovation and climate finance (supplemental figure S5), positive subsidies, and feed-in tariffs that guarantee an above-market price for renewable energy producers.

A call to action

Recent years have seen an unprecedented trend in scientists speaking out on the climate crisis. We applaud this trend and view it as a natural consequence of scientists being citizens concerned about the preservation of the planet for future generations (Nelson and Vucetich 2009). When backed by sound and transparent scientific arguments, the potential for scientists to educate the public and speak truth to power can be a driving force for the needed policy shifts. Indeed, vocal and articulate scientists played a key role in bringing issues such as nuclear annihilation and ozone depletion to the fore. In this spirit, we implore our fellow scientists to speak out on climate and other environmental issues. In addition to speaking out, some researchers have argued that the situation is so dire that we are at the point where peaceful civil disobedience by scientists is needed (Capstick et al. 2022).

As has been demonstrated by the surge in yearly climate disasters, we are now in a major climate crisis and global catastrophe with far worse in store if we continue with business as usual. As such, there is more at stake today than at any time since the advent of the stable climate system that has supported us for more than 10,000 years. Here we stand at the precipice, with the opportunity to make such an immense difference for life on Earth. Approximately one hundred billion people have lived and died over the 2-million-year history of humans on Earth (Curtin 2007), and there are potentially

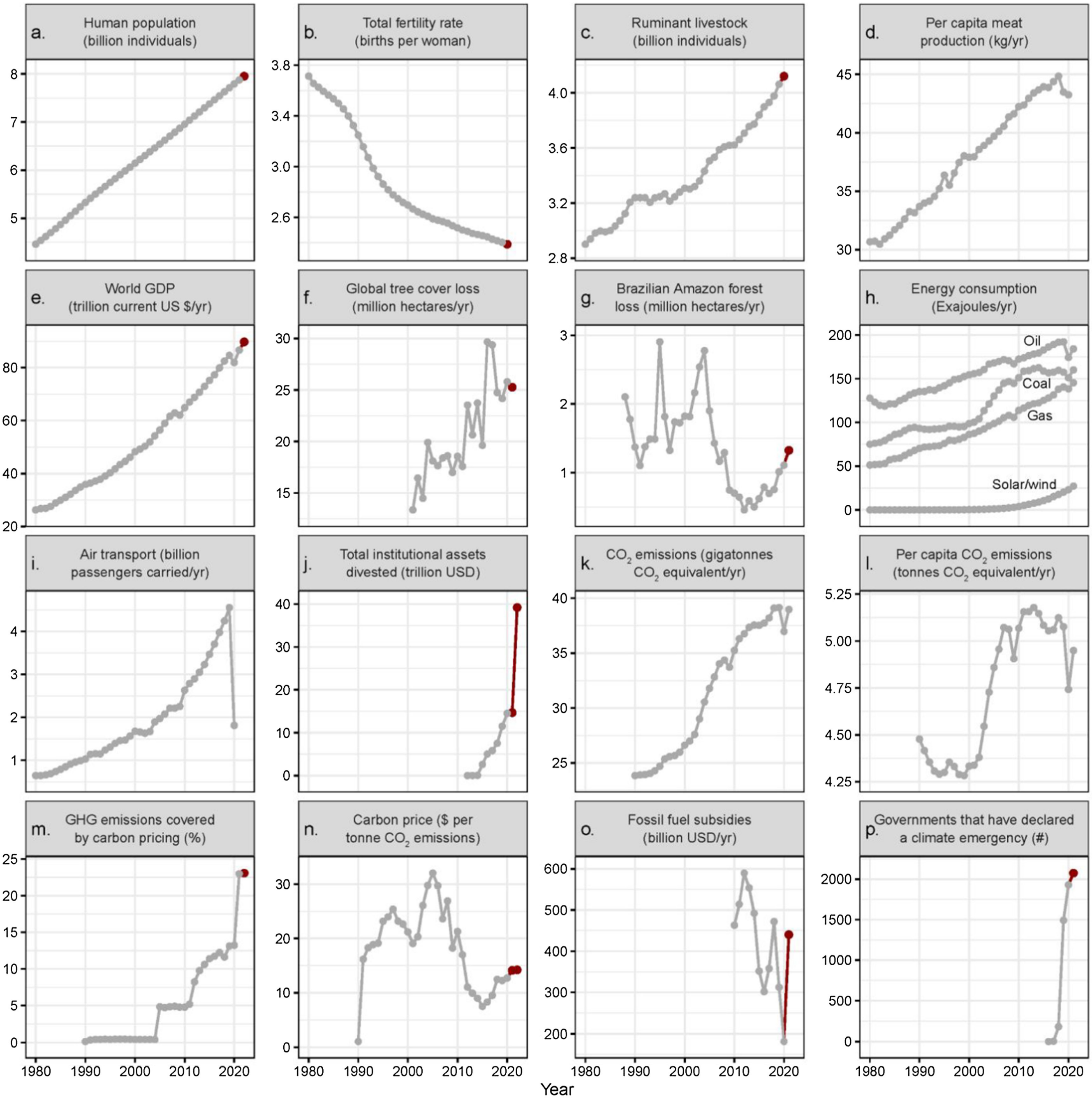

Figure 2. Time series of climate-related human activities. Data obtained since the publication of Ripple and colleagues (2021) are shown in red (dark gray in print). In panel (f), tree cover loss does not account for forest gain and includes loss due to any cause. For panel (h), hydroelectricity and nuclear energy are shown in supplemental figure S1. In panel (j), assets divested reflects total assets under management based on institutional commitments. Sources and additional details about each variable are provided in supplemental file s1.

trillions of human beings who will someday exist whose fate depends on the choices we make today. The very future of humanity depends on the creativity, moral fiber, and perseverance of the 8 billion of us on the planet now. Rather than lose hope, we must equitably reduce ecological overshoot and immediately pursue massive-scale climate change mitigation and adaptation. This is the only way we can limit the near-term damage, preserve nature, avoid untold human suffering, and give future generations the opportunities they deserve.

Project websites

The World Scientists' Warning of a Climate Emergency paper (Ripple et al. 2020) now has more than 14,700

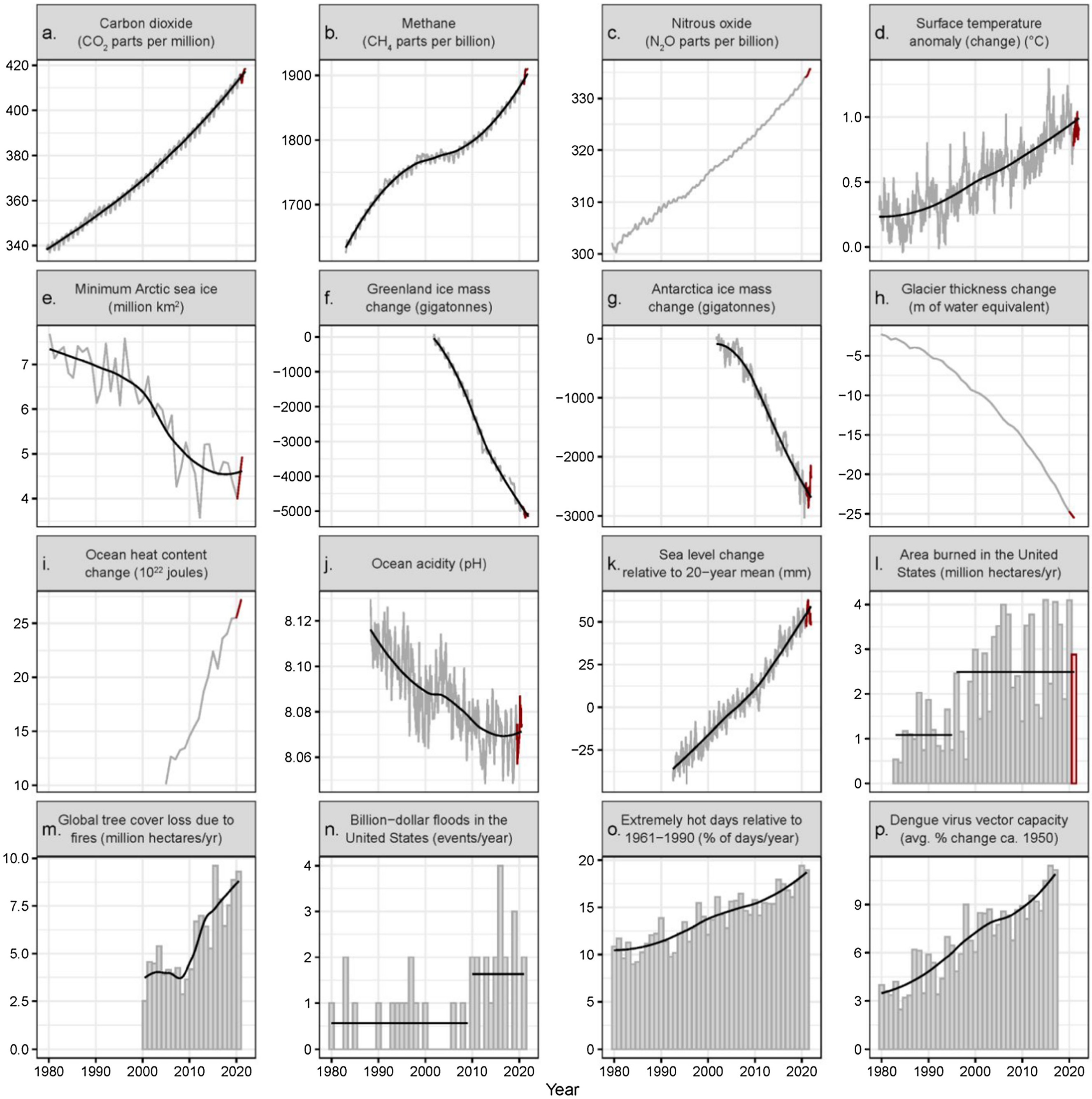

Figure 3. Time series of climate-related responses. Data obtained after the publication of Ripple and colleagues (2021) are shown in red (dark gray in print). For area burned (l) and billion-dollar flood frequency (n) in the United States, black horizontal lines show changepoint model estimates, which allow for abrupt shifts (see supplement). For other variables with relatively high variability, local regression trendlines are shown in black. Variables were measured at various frequencies (e.g., annual, monthly, weekly). Labels on the x-axis correspond to midpoints of years. Billion-dollar flood frequency (n) is likely influenced by exposure and vulnerability in addition to climate change. Sources and additional details about each variable are provided in supplemental file S1.

signatories from 158 countries, and we continue to collect signatures from scientists. To sign or learn more, visit the Alliance of World Scientists website at https://scientistswarning.forestry.oregonstate.edu. To read about science-based advocacy and view "A Scientist's Warning," a new documentary film on scientists speaking out, visit www.scientistswarningfilm.org.

Acknowledgements

We thank Michael Mann, Franz Baumann, Kelly Patrick Gerling, William H. Calvin, Katherine Gaubard, Joseph McNulty, and

*Table 1. Recent climate disasters in 2022.**

Timeframe	Climate disaster
January–September 2022	Many rivers in Europe have run low or dried up partly because of the worst drought in 500 years and intense heat waves. Climate change has likely played a significant role in this crisis by increasing the frequency and intensity of droughts and heat waves.
February 2022	La Niña and climate change contributed to record-breaking rainfall on the east coast of Australia. This led to flooding that damaged thousands of properties and killed eight people.
February–March 2022	Record-breaking flooding occurred along the northeastern coast of Australia, leading to standing water, which, in turn, promoted the spread of mosquitoes that carry the Japanese encephalitis virus. Such flooding is likely becoming more common because of climate change.
February–July 2022	The number of people affected by drought in Kenya, Somalia, and Ethiopia who have limited access to safe water increased from 9.5 million to 16.2 million. This increasing drought severity may be at least partly due to climate change (Ghebrezgabher et al. 2016).
March 2022	A severe drought in the Southern Plains of the United States put the winter wheat crop at risk. Although droughts are complex phenomena with many possible causes, increasing drought intensity has been linked to climate change (Mukherjee et al. 2018).
March–April 2022	A deadly heat wave occurred in India and Pakistan, killing at least 90 people and contributing to widespread crop losses and wildfires. It was estimated that climate change made this event 30 times more likely to occur.
April 2022	Climate change likely contributed to extreme rainfall in Eastern South Africa, which triggered flooding and landslides that killed at least 435 people and affected more than 40,000 people.
April–June 2022	Widespread dust storms in the Middle East led to thousands of people being hospitalized; such dust storms may be increasing in frequency because of climate change.
May 2022	Extremely heavy rainfall in northeastern Brazil resulted in landslides and flooding that killed at least 100 people. Climate change may be responsible for the increasing frequency of extreme rainfall.
June 2022	A severe storm in Yellowstone (United States) caused the Gardner River and Lamar River to overflow, destroying parts of various roads in Yellowstone National Park. Such extreme flooding could be increasing in frequency because of climate change.
June 2022	Several countries in Western Europe experienced a record-breaking heat wave. This heat wave contributed to major wildfires in Spain and Germany. Many other parts of the Northern Hemisphere also experienced extreme heat; for example, temperatures reached 104.4 degrees Fahrenheit in Isesaki, Japan—an all-time record for the country. Similarly, a heat dome in the United States contributed to record-breaking temperatures. Other affected countries include Finland, Iran, Norway, and Italy. In general, extreme heat is becoming more common because of climate change (Luber and McGeehin 2008).
June 2022	Following extreme heat, China experienced record-breaking rainfall, which may be linked to climate change.
June 2022	Bangladesh experienced the worst monsoon flooding in 100 years, killing at least 26 people. This flooding is likely at least partly due to climate change causing monsoons to become more variable.
June–July 2022	Extreme rainfall led to flooding in some parts of New South Wales, Australia. Sydney is currently on track to experience the wettest year on record. It is likely that climate change contributed at least partly to this rainfall and flooding.
June–August 2022	Deadly floods in Pakistan have killed more than 1,000 people and affected roughly 33 million people, including 16 million children, since mid-June. Impacts include surging rates of dengue fever, gastric infections, and malaria. These floods may be at least partly related to climate change causing monsoon rainfall to become more intense.
June–August 2022	China experienced an extraordinary heat wave, which may be the most severe that has ever been recorded globally. Such events are likely becoming more common because of climate change. The extreme heat contributed to large-scale crop failures and wildfires, in addition to exacerbating a major drought that caused 66 rivers to dry up and led to a significant decline in hydroelectricity generation.
August–September 2022	California and other parts of the Western United States faced extremely hot temperatures because of a heat dome, which caused seven firefighters to be hospitalized with heat-related injuries. The effects of the heat dome may have been worsened by climate change.
September–October 2022	In the United States, Hurricane Ian caused damage across many parts of Florida and the Carolinas, killing more than 100 people and leaving at least 2.5 million without electrical power. Ian is one of the costliest and strongest hurricanes to ever hit the United States. Climate change is likely causing strong and rapidly intensifying storms such as Ian to become more common.

*Here, we list numerous recent disasters that may be at least partly related to climate change. This list is not intended to be exhaustive. Because of the recent nature of these events, our sources often include news media articles. For each event, we generally provide references indicating that the likelihood or strength of such an event may have increased because of anthropogenic climate change. References to scientific articles are given directly in the table, and links to news articles are provided in supplemental file S1.
Note: Some of these climate disasters may be at least partly related to changes in jet streams (Stendel et al. 2021, Rousi et al. 2022).

Karen Wolfgang for providing helpful suggestions. Partial funding was received from the CO2 Foundation, Karen Josephson, Peter Stoel, and Roger Worthington.

Supplemental material

Supplemental data are available at *BIOSCI* online.

The methods and details of planetary vital sign variables used in this report along with other discussion appear in supplemental file S1 of this article. A list of the scientist signatories for Ripple and colleagues (2020) as of 25 August 2022 appears in supplemental file S2 of this article. Note that these signatures are not for the current article.

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Comment

Climate tipping points — too risky to bet against

Timothy M. Lenton, Johan Rockström, Owen Gaffney, Stefan Rahmstorf, Katherine Richardson, Will Steffen & Hans Joachim Schellnhuber

The growing threat of abrupt and irreversible climate changes must compel political and economic action on emissions.

Politicians, economists and even some natural scientists have tended to assume that tipping points[1] in the Earth system — such as the loss of the Amazon rainforest or the West Antarctic ice sheet — are of low probability and little understood. Yet evidence is mounting that these events could be more likely than was thought, have high impacts and are interconnected across different biophysical systems, potentially committing the world to long-term irreversible changes.

Here we summarize evidence on the threat of exceeding tipping points, identify knowledge gaps and suggest how these should be plugged. We explore the effects of such large-scale changes, how quickly they might unfold and whether we still have any control over them.

In our view, the consideration of tipping points helps to define that we are in a climate emergency and strengthens this year's chorus of calls for urgent climate action — from schoolchildren to scientists, cities and countries.

The Intergovernmental Panel on Climate Change (IPCC) introduced the idea of tipping points two decades ago. At that time, these 'large-scale discontinuities' in the climate system were considered likely only if global warming exceeded 5 °C above pre-industrial levels. Information summarized in the two most recent IPCC Special Reports (published in 2018 and in September this year)[2,3] suggests that tipping points could be exceeded even between 1 and 2 °C of warming (see 'Too close for comfort').

If current national pledges to reduce greenhouse-gas emissions are implemented — and that's a big 'if' — they are likely to result in at least 3 °C of global warming. This is despite the goal of the 2015 Paris agreement to limit warming to well below 2 °C. Some economists, assuming that climate tipping points are of very low probability (even if they would be catastrophic), have suggested that 3 °C warming is optimal from a cost–benefit perspective. However, if tipping points are looking more likely, then the 'optimal policy' recommendation of simple cost–benefit climate-economy models[4] aligns with those of the recent IPCC report[2]. In other words, warming must be limited to 1.5 °C. This requires an emergency response.

Ice collapse

We think that several cryosphere tipping points are dangerously close, but mitigating greenhouse-gas emissions could still slow down the inevitable accumulation of impacts and help us to adapt.

Research in the past decade has shown that the Amundsen Sea embayment of West Antarctica might have passed a tipping point[3]: the 'grounding line' where ice, ocean and bedrock meet is retreating irreversibly. A model study shows[5] that when this sector collapses, it could destabilize the rest of the West Antarctic ice sheet like toppling dominoes — leading to about 3 metres of sea-level rise on a timescale of centuries to millennia. Palaeo-evidence shows that such widespread collapse of the West Antarctic ice sheet has occurred repeatedly in the past.

The latest data show that part of the East Antarctic ice sheet — the Wilkes Basin — might be similarly unstable[3]. Modelling work suggests that it could add another 3–4 m to sea level on timescales beyond a century.

The Greenland ice sheet is melting at an accelerating rate[3]. It could add a further 7 m to sea level over thousands of years if it passes a particular threshold. Beyond that, as the elevation of the ice sheet lowers, it melts further, exposing the surface to ever-warmer air. Models suggest that the Greenland ice sheet could be doomed at 1.5 °C of warming[3], which could happen as soon as 2030.

Thus, we might already have committed future generations to living with sea-level rises of around 10 m over thousands of years[3]. But that timescale is still under our control. The rate of melting depends on the magnitude of warming above the tipping point. At 1.5 °C, it could take 10,000 years to unfold[3]; above 2 °C it could take less than 1,000 years[6].

An aeroplane flies over a glacier in the Wrangell St Elias National Park in Alaska.

FRANS LANTING/NAT. GEO. IMAGE COLLECTION

Researchers need more observational data to establish whether ice sheets are reaching a tipping point, and require better models constrained by past and present data to resolve how soon and how fast the ice sheets could collapse.

Whatever those data show, action must be taken to slow sea-level rise. This will aid adaptation, including the eventual resettling of large, low-lying population centres.

A further key impetus to limit warming to 1.5 °C is that other tipping points could be triggered at low levels of global warming. The latest IPCC models projected a cluster of abrupt shifts[7] between 1.5 °C and 2 °C, several of which involve sea ice. This ice is already shrinking rapidly in the Arctic, indicating that, at 2 °C of warming, the region has a 10–35% chance[3] of becoming largely ice-free in summer.

"The clearest emergency would be if we were approaching a global cascade of tipping points."

Biosphere boundaries

Climate change and other human activities risk triggering biosphere tipping points across a range of ecosystems and scales (see 'Raising the alarm').

Ocean heatwaves have led to mass coral bleaching and to the loss of half of the shallow-water corals on Australia's Great Barrier Reef. A staggering 99% of tropical corals are projected[2] to be lost if global average temperature rises by 2 °C, owing to interactions between warming, ocean acidification and pollution. This would represent a profound loss of marine biodiversity and human livelihoods.

As well as undermining our life-support system, biosphere tipping points can trigger abrupt carbon release back to the atmosphere. This can amplify climate change and reduce remaining emission budgets.

Deforestation and climate change are destabilizing the Amazon — the world's largest rainforest, which is home to one in ten known species. Estimates of where an Amazon tipping point could lie range from 40% deforestation to just 20% forest-cover loss[8]. About 17% has been lost since 1970. The rate of deforestation varies with changes in policy. Finding the tipping point requires models that include deforestation and climate change as interacting drivers, and that incorporate fire and climate feedbacks as interacting tipping mechanisms across scales.

With the Arctic warming at least twice as quickly as the global average, the boreal forest in the subarctic is increasingly vulnerable. Already, warming has triggered large-scale insect disturbances and an increase

ALEXIS ROSENFELD/GETTY

Bleached corals on a reef near the island of Moorea in French Polynesia in the South Pacific.

in fires that have led to dieback of North American boreal forests, potentially turning some regions from a carbon sink to a carbon source[9]. Permafrost across the Arctic is beginning to irreversibly thaw and release carbon dioxide and methane — a greenhouse gas that is around 30 times more potent than CO_2 over a 100-year period.

Researchers need to improve their understanding of these observed changes in major ecosystems, as well as where future tipping points might lie. Existing carbon stores and potential releases of CO_2 and methane need better quantification.

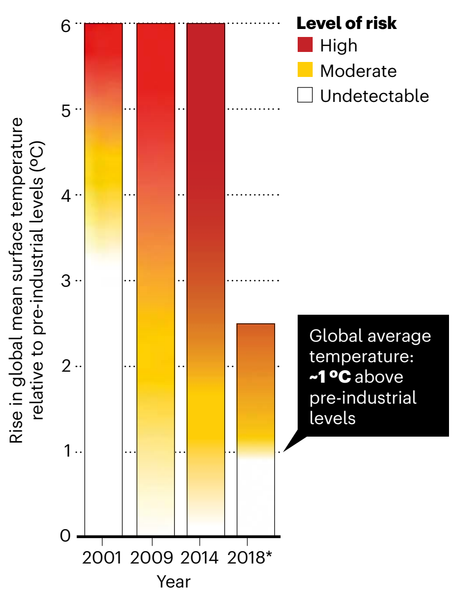
The world's remaining emissions budget for a 50:50 chance of staying within 1.5 °C of warming is only about 500 gigatonnes (Gt) of CO_2. Permafrost emissions could take an estimated 20% (100 Gt CO_2) off this budget[10], and that's without including methane from deep permafrost or undersea hydrates. If forests are close to tipping points, Amazon dieback could release another 90 Gt CO_2 and boreal forests a further 110 Gt CO_2 (ref. 11). With global total CO_2 emissions still at more than 40 Gt per year, the remaining budget could be all but erased already.

Global cascade

In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, 'hothouse' climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature. Alternatively, strong cloud feedbacks could cause a global tipping point[12,13].

TOO CLOSE FOR COMFORT

Abrupt and irreversible changes in the climate system have become a higher risk at lower global average temperature rise. This has been suggested for large events such as the partial disintegration of the Antarctic ice sheet.



*The 2018 IPCC *Special Report: Global Warming of 1.5 °C* focuses on the temperature range up to 2.5 °C.

SOURCE: IPCC AND J. B. SMITH *ET AL. PROC. NATL ACAD. SCI. USA* **106**, 4133–4137 (2009)

We argue that cascading effects might be common. Research last year[14] analysed 30 types of regime shift spanning physical climate and ecological systems, from collapse of the West Antarctic ice sheet to a switch from rainforest to savanna. This indicated that exceeding tipping points in one system can increase the risk of crossing them in others. Such links were found for 45% of possible interactions[14].

In our view, examples are starting to be observed. For example, Arctic sea-ice loss is amplifying regional warming, and Arctic warming and Greenland melting are driving an influx of fresh water into the North Atlantic. This could have contributed to a 15% slowdown[15] since the mid-twentieth century of the Atlantic Meridional Overturning Circulation (AMOC) , a key part of global heat and salt transport by the ocean[3]. Rapid melting of the Greenland ice sheet and further slowdown of the AMOC could destabilize the West African monsoon, triggering drought in Africa's Sahel region. A slowdown in the AMOC could also dry the Amazon, disrupt the East Asian monsoon and cause heat to build up in the Southern Ocean, which could accelerate Antarctic ice loss.

The palaeo-record shows global tipping, such as the entry into ice-age cycles 2.6 million years ago and their switch in amplitude and frequency around one million years ago, which models are only just capable of simulating. Regional tipping occurred repeatedly within and at the end of the last ice age, between 80,000 and 10,000 years ago (the Dansgaard–Oeschger and Heinrich events). Although this is not directly applicable to the present interglacial period, it highlights that the Earth system has been unstable across multiple timescales before, under relatively weak forcing caused by changes in Earth's orbit. Now we are strongly forcing the system, with atmospheric CO_2 concentration and global temperature increasing at rates that are an order of magnitude higher than those during the most recent deglaciation.

Atmospheric CO_2 is already at levels last seen around four million years ago, in the Pliocene epoch. It is rapidly heading towards levels last seen some 50 million years ago – in the Eocene – when temperatures were up to 14 °C higher than they were in pre-industrial times. It is challenging for climate models to simulate such past 'hothouse' Earth states. One possible explanation is that the models have been missing a key tipping point: a cloud-resolving model published this year suggests that the abrupt break-up of stratocumulus cloud above about 1,200 parts per million of CO_2 could have resulted in roughly 8 °C of global warming[12].

Some early results from the latest climate models – run for the IPCC's sixth assessment report, due in 2021 – indicate a much larger climate sensitivity (defined as the temperature response to doubling of atmospheric CO_2) than in previous models. Many more results are pending and further investigation is required, but to us, these preliminary results hint that a global tipping point is possible.

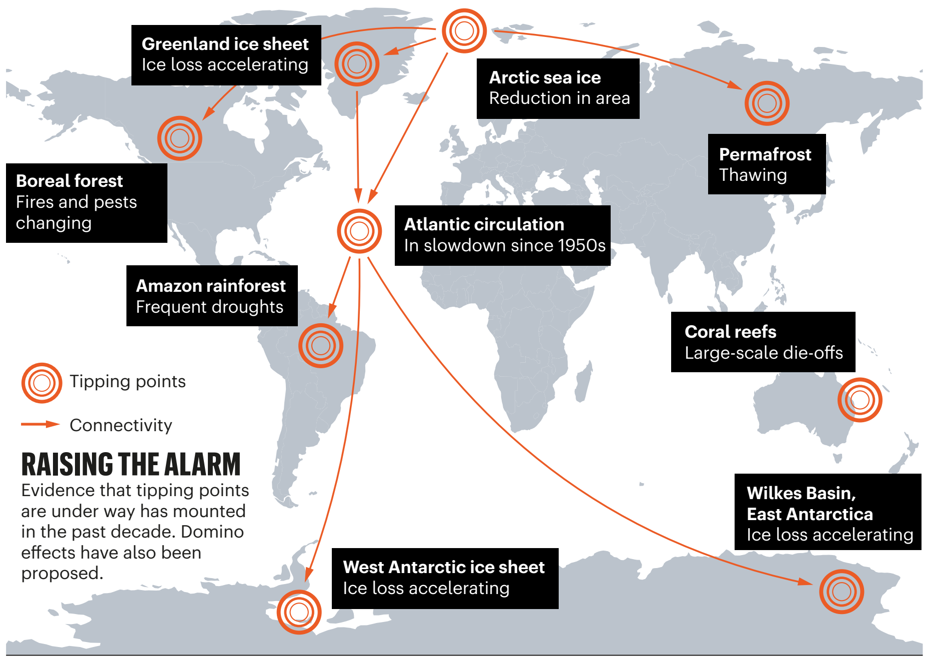
To address these issues, we need models that capture a richer suite of couplings and feedbacks in the Earth system, and we need more data – present and past – and better ways to use them. Improving the ability of models to capture known past abrupt climate changes and 'hothouse' climate states should increase confidence in their ability to forecast these.

EMERGENCY: DO THE MATHS

We define emergency (E) as the product of risk and urgency. Risk (R) is defined by insurers as probability (p) multiplied by damage (D). Urgency (U) is defined in emergency situations as reaction time to an alert (τ) divided by the intervention time left to avoid a bad outcome (T). Thus:

$$E = R \times U = p \times D \times \tau / T$$

The situation is an emergency if both risk and urgency are high. If reaction time is longer than the intervention time left ($\tau/T > 1$), we have lost control.



RAISING THE ALARM
Evidence that tipping points are under way has mounted in the past decade. Domino effects have also been proposed.

SOURCE: T. M. LENTON *ET AL.*

Some scientists counter that the possibility of global tipping remains highly speculative. It is our position that, given its huge impact and irreversible nature, any serious risk assessment must consider the evidence, however limited our understanding might still be. To err on the side of danger is not a responsible option.

If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization. No amount of economic cost–benefit analysis is going to help us. We need to change our approach to the climate problem.

Act now

In our view, the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute (see 'Emergency: do the maths').

We argue that the intervention time left to prevent tipping could already have shrunk towards zero, whereas the reaction time to achieve net zero emissions is 30 years at best. Hence we might already have lost control of whether tipping happens. A saving grace is that the rate at which damage accumulates from tipping – and hence the risk posed – could still be under our control to some extent.

The stability and resilience of our planet is in peril. International action – not just words – must reflect this.

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Correction

The figure 'Too close for comfort' in this Comment incorrectly synthesized and interpreted information from the IPCC. The graph labelled the temperatures as absolute, rather than rises; misrepresented the levels of risk; misinterpreted information as coming from a 2007 IPCC report; extrapolated the focus of a 2018 report; and was not clear about the specific sources of the information. The graphic has been extensively modified online to correct these errors.

PNAS PERSPECTIVE OPEN ACCESS

Climate Endgame: Exploring catastrophic climate change scenarios

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Edited by Kerry Emanuel, Massachusetts Institute of Technology, Cambridge, MA; received May 20, 2021; accepted March 25, 2022

Prudent risk management requires consideration of bad-to-worst-case scenarios. Yet, for climate change, such potential futures are poorly understood. Could anthropogenic climate change result in worldwide societal collapse or even eventual human extinction? At present, this is a dangerously underexplored topic. Yet there are ample reasons to suspect that climate change could result in a global catastrophe. Analyzing the mechanisms for these extreme consequences could help galvanize action, improve resilience, and inform policy, including emergency responses. We outline current knowledge about the likelihood of extreme climate change, discuss why understanding bad-to-worst cases is vital, articulate reasons for concern about catastrophic outcomes, define key terms, and put forward a research agenda. The proposed agenda covers four main questions: 1) What is the potential for climate change to drive mass extinction events? 2) What are the mechanisms that could result in human mass mortality and morbidity? 3) What are human societies' vulnerabilities to climate-triggered risk cascades, such as from conflict, political instability, and systemic financial risk? 4) How can these multiple strands of evidence—together with other global dangers—be usefully synthesized into an "integrated catastrophe assessment"? It is time for the scientific community to grapple with the challenge of better understanding catastrophic climate change.

catastrophic climate change | climate change | Earth system trajectories | Anthropocene | tipping elements

How bad could climate change get? As early as 1988, the landmark Toronto Conference declaration described the ultimate consequences of climate change as potentially "second only to a global nuclear war." Despite such proclamations decades ago, climate catastrophe is relatively under-studied and poorly understood.

The potential for catastrophic impacts depends on the magnitude and rate of climate change, the damage inflicted on Earth and human systems, and the vulnerability and response of those affected systems. The extremes of these areas, such as high temperature rise and cascading impacts, are underexamined. As noted by the Intergovernmental Panel on Climate Change (IPCC), there have been few quantitative estimates of global aggregate impacts from warming of 3 °C or above (1). Text mining of IPCC reports similarly found that coverage of temperature rises of 3 °C or higher is underrepresented relative to their likelihood (2). Text-mining analysis also suggests that over time the coverage of IPCC reports has shifted towards temperature rise of 2 °C and below https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2022EF002876. Research has focused on the impacts of 1.5 °C and 2 °C, and studies of how climate impacts could cascade or trigger larger crises are sparse.

A thorough risk assessment would need to consider how risks spread, interact, amplify, and are aggravated by human responses (3), but even simpler "compound hazard" analyses of interacting climate hazards and drivers are underused. Yet this is how risk unfolds in the real world. For example, a cyclone destroys electrical infrastructure, leaving a population vulnerable to an ensuing deadly heat wave (4). Recently, we have seen compound hazards emerge between climate change and the COVID-19 pandemic (5). As the IPCC notes, climate risks are becoming more complex and difficult to manage, and are cascading across regions and sectors (6).

Why the focus on lower-end warming and simple risk analyses? One reason is the benchmark of the international targets: the Paris Agreement goal of limiting warming to well below 2 °C, with an aspiration of 1.5 °C. Another reason is the culture of climate science to "err on the side of least drama" (7), to not to be alarmists, which can be compounded by the consensus processes of the IPCC (8). Complex risk assessments, while more realistic, are also more difficult to do.

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Author contributions: L.K. designed research; L.K., C.X., J.D., K.L.E., G.G., T.A.K., J.R., M.S., H.J.S., W.S., and T.M.L. performed research; L.K., C.X., J.D., K.L.E., T.A.K., J.R., M.S., H.J.S., W.S., and T.M.L. analyzed data; and L.K., C.X., J.D., K.L.E., G.G., T.A.K., J.R., M.S., H.J.S., W.S., and T.M.L. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at http://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2108146119/-/DCSupplemental.

Published August 1, 2022.

This caution is understandable, yet it is mismatched to the risks and potential damages posed by climate change. We know that temperature rise has "fat tails": low-probability, high-impact extreme outcomes (9). Climate damages are likely to be nonlinear and result in an even larger tail (10). Too much is at stake to refrain from examining high-impact low-likelihood scenarios. The COVID-19 pandemic has underlined the need to consider and prepare for infrequent, high-impact global risks, and the systemic dangers they can spark. Prudent risk management demands that we thoroughly assess worst-case scenarios.

Our proposed "Climate Endgame" research agenda aims to direct exploration of the worst risks associated with anthropogenic climate change. To introduce it, we summarize existing evidence on the likelihood of extreme climate change, outline why exploring bad-to-worst cases is vital, suggest reasons for catastrophic concern, define key terms, and then explain the four key aspects of the research agenda.

Worst-Case Climate Change

Despite 30 y of efforts and some progress under the United Nations Framework Convention on Climate Change (UNFCCC) anthropogenic greenhouse gas (GHG) emissions continue to increase. Even without considering worst-case climate responses, the current trajectory puts the world on track for a temperature rise between 2.1 °C and 3.9 °C by 2100 (11). If all 2030 nationally determined contributions are fully implemented, warming of 2.4 °C (1.9 °C to 3.0 °C) is expected by 2100. Meeting all long-term pledges and targets could reduce this to 2.1 °C (1.7 °C to 2.6 °C) (12). Even these optimistic assumptions lead to dangerous Earth system trajectories. Temperatures of more than 2 °C above preindustrial values have not been sustained on Earth's surface since before the Pleistocene Epoch (or more than 2.6 million years ago) (13).

Even if anthropogenic GHG emissions start to decline soon, this does not rule out high future GHG concentrations or extreme climate change, particularly beyond 2100. There are feedbacks in the carbon cycle and potential tipping points that could generate high GHG concentrations (14) that are often missing from models. Examples include Arctic permafrost thawing that releases methane and CO_2 (15), carbon loss due to intense droughts and fires in the Amazon (16), and the apparent slowing of dampening feedbacks such as natural carbon sink capacity (17, 18). These are likely to not be proportional to warming, as is sometimes assumed. Instead, abrupt and/or irreversible changes may be triggered at a temperature threshold. Such changes are evident in Earth's geological record, and their impacts cascaded across the coupled climate–ecological–social system (19). Particularly worrying is a "tipping cascade" in which multiple tipping elements interact in such a way that tipping one threshold increases the likelihood of tipping another (20). Temperature rise is crucially dependent on the overall dynamics of the Earth system, not just the anthropogenic emissions trajectory.

The potential for tipping points and higher concentrations despite lower anthropogenic emissions is evident in existing models. Variability among the latest Coupled Model Intercomparison Project Phase 6 (CMIP6) climate models results in overlap in different scenarios. For example, the top (75th) quartile outcome of the "middle-of-the-road" scenario (Shared Socioeconomic Pathway 3-7.0, or SSP3-7.0) is substantially hotter than the bottom (25th) quartile of the highest emissions (SSP5-8.5) scenario. Regional temperature differences between models can exceed 5 °C to 6 °C, particularly in polar areas where various tipping points can occur (*SI Appendix*).

There are even more uncertain feedbacks, which, in a very worst case, might amplify to an irreversible transition into a "Hothouse Earth" state (21) (although there may be negative feedbacks that help buffer the Earth system). In particular, poorly understood cloud feedbacks might trigger sudden and irreversible global warming (22). Such effects remain underexplored and largely speculative "unknown unknowns" that are still being discovered. For instance, recent simulations suggest that stratocumulus cloud decks might abruptly be lost at CO_2 concentrations that could be approached by the end of the century, causing an additional ∼8 °C global warming (23). Large uncertainties about dangerous surprises are reasons to prioritize rather than neglect them.

Recent findings on equilibrium climate sensitivity (ECS) (14, 24) underline that the magnitude of climate change is uncertain even if we knew future GHG concentrations. According to the IPCC, our best estimate for ECS is a 3 °C temperature rise per doubling of CO_2, with a "likely" range of (66 to 100% likelihood) of 2.5 °C to 4 °C. While an ECS below 1.5 °C was essentially ruled out, there remains an 18% probability that ECS could be greater than 4.5 °C (14). The distribution of ECS is "heavy tailed," with a higher probability of very high values of ECS than of very low values.

There is significant uncertainty over future anthropogenic GHG emissions as well. Representative Concentration Pathway 8.5 (RCP8.5, now SSP5-8.5), the highest emissions pathway used in IPCC scenarios, most closely matches cumulative emissions to date (25). This may not be the case going forward, because of falling prices of renewable energy and policy responses (26). Yet, there remain reasons for caution. For instance, there is significant uncertainty over key variables such as energy demand and economic growth. Plausibly higher economic growth rates could make RCP8.5 35% more likely (27).

Why Explore Climate Catastrophe?

Why do we need to know about the plausible worst cases? First, risk management and robust decision-making under uncertainty requires knowledge of extremes. For example, the minimax criterion ranks policies by their worst outcomes (28). Such an approach is particularly appropriate for areas characterized by high uncertainties and tail risks. Emissions trajectories, future concentrations, future warming, and future impacts are all characterized by uncertainty. That is, we can't objectively prescribe probabilities to different outcomes (29). Climate damages lie within the realm of "deep uncertainty": We don't know the probabilities attached to different outcomes, the exact chain of cause and effect that will lead to outcomes, or even the range, timing, or desirability of outcomes (, 30). Uncertainty, deep or not, should motivate precaution and vigilance, not complacency.

Catastrophic impacts, even if unlikely, have major implications for economic analysis, modeling, and society's responses

(31, 32). For example, extreme warming and the consequent damages can significantly increase the projected social cost of carbon (31). Understanding the vulnerability and responses of human societies can inform policy making and decision-making to prevent systemic crises. Indicators of key variables can provide early warning signals (33).

Knowing the worst cases can compel action, as the idea of "nuclear winter" in 1983 galvanized public concern and nuclear disarmament efforts. Exploring severe risks and higher-temperature scenarios could cement a recommitment to the 1.5 °C to 2 °C guardrail as the "least unattractive" option (34).

Understanding catastrophic climate scenarios can also inform policy interventions, including last-resort emergency measures like solar radiation management (SRM), the injection of aerosols into the stratosphere to reflect sunlight (35). Whether to resort to such measures depends on the risk profiles of both climate change and SRM scenarios. One recent analysis of the potential catastrophic risk of stratospheric aerosol injection (SAI) found that the direct and systemic impacts are under-studied (36). The largest danger appears to come from "termination shock": abrupt and rapid warming if the SAI system is disrupted. Hence, SAI shifts the risk distribution: The median outcome may be better than the climate change it is offsetting, but the tail risk could be worse than warming (36).

There are other interventions that a better understanding of catastrophic climate change could facilitate. For example, at the international level, there is the potential for a "tail risk treaty": an agreement or protocol that activates stronger commitments and mechanisms when early-warning indicators of potential abrupt change are triggered.

The Potential for Climate Catastrophe

There are four key reasons to be concerned over the potential of a global climate catastrophe. First, there are warnings from history. Climate change (either regional or global) has played a role in the collapse or transformation of numerous previous societies (37) and in each of the five mass extinction events in Phanerozoic Earth history (38). The current carbon pulse is occurring at an unprecedented geological speed and, by the end of the century, may surpass thresholds that triggered previous mass extinctions (39, 40). The worst-case scenarios in the IPCC report project temperatures by the 22nd century that last prevailed in the Early Eocene, reversing 50 million years of cooler climates in the space of two centuries (41).

This is particularly alarming, as human societies are locally adapted to a specific climatic niche. The rise of large-scale, urbanized agrarian societies began with the shift to the stable climate of the Holocene ∼12,000 y ago (42). Since then, human population density peaked within a narrow climatic envelope with a mean annual average temperature of ∼13 °C. Even today, the most economically productive centers of human activity are concentrated in those areas (43). The cumulative impacts of warming may overwhelm societal adaptive capacity.

Second, climate change could directly trigger other catastrophic risks, such as international conflict, or exacerbate infectious disease spread, and spillover risk. These could be potent extreme threat multipliers.

Third, climate change could exacerbate vulnerabilities and cause multiple, indirect stresses (such as economic damage, loss of land, and water and food insecurity) that coalesce into system-wide synchronous failures. This is the path of systemic risk. Global crises tend to occur through such reinforcing "synchronous failures" that spread across countries and systems, as with the 2007–2008 global financial crisis (44). It is plausible that a sudden shift in climate could trigger systems failures that unravel societies across the globe.

The potential of systemic climate risk is marked: The most vulnerable states and communities will continue to be the hardest hit in a warming world, exacerbating inequities. Fig. 1 shows how projected population density intersects with extreme >29 °C mean annual temperature (MAT) (such temperatures are currently restricted to only 0.8% of Earth's land surface area). Using the medium-high scenario of emissions and population growth (SSP3-7.0 emissions, and SSP3 population growth), by 2070, around 2 billion people are expected to live in these extremely hot areas. Currently, only 30 million people live in hot places, primarily in the Sahara Desert and Gulf Coast (43).

Extreme temperatures combined with high humidity can negatively affect outdoor worker productivity and yields of major cereal crops. These deadly heat conditions could significantly affect populated areas in South and southwest Asia(47).

Fig. 2 takes a political lens on extreme heat, overlapping SSP3-7.0 or SSP5-8.5 projections of >29 °C MAT circa 2070, with the Fragile States Index (a measurement of the instability of states). There is a striking overlap between currently vulnerable states and future areas of extreme warming. If current political fragility does not improve significantly in the coming decades, then a belt of instability with potentially serious ramifications could occur.

Finally, climate change could irrevocably undermine humanity's ability to recover from another cataclysm, such as nuclear war. That is, it could create significant latent risks (Table 1): Impacts that may be manageable during times of stability become dire when responding to and recovering from catastrophe. These different causes for catastrophic concern are interrelated and must be examined together.

Defining the Key Terms

Although bad-to-worst case scenarios remain underexplored in the scientific literature, statements labeling climate change as catastrophic are not uncommon. UN Secretary-General António Guterres called climate change an "existential threat." Academic studies have warned that warming above 5 °C is likely to be "beyond catastrophic" (50), and above 6 °C constitutes "an indisputable global catastrophe" (9).

Current discussions over climate catastrophe are undermined by unclear terminology. The term "catastrophic climate change" has not been conclusively defined. An existential risk is usually defined as a risk that cause an enduring and significant loss of long-term human potential (51, 52). This existing definition is deeply ambiguous and requires societal discussion and specification of long-term human values (52). While a democratic exploration of values is welcome, it is not

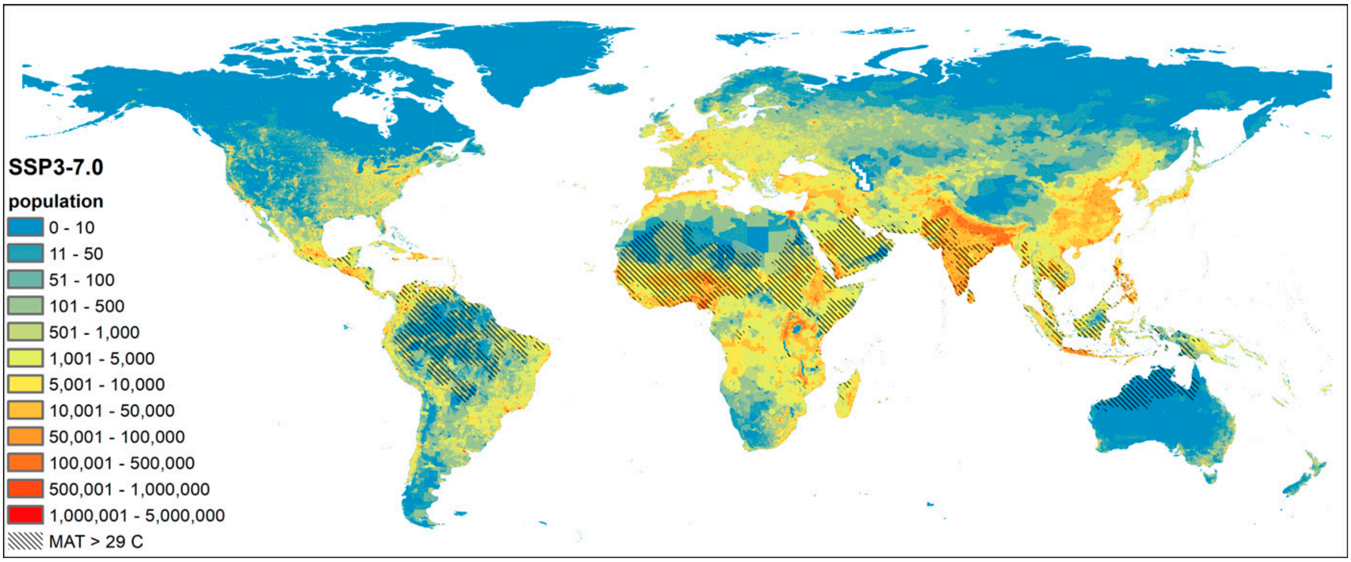

Fig. 1. Overlap between future population distribution and extreme heat. CMIP6 model data [from nine GCM models available from the WorldClim database (45)] were used to calculate MAT under SSP3-7.0 during around 2070 (2060–2080) alongside Shared SSP3 demographic projections to ∼2070 (46). The shaded areas depict regions where MAT exceeds 29 °C, while the colored topography details the spread of population density.

required to understand pathways to human catastrophe or extinction (52). For now, the existing definition is not a solid foundation for a scientific inquiry.

We offer clarified working definitions of such terms in Table 1. This is an initial step toward creating a lexicon for global calamity. Some of the terms, such as what constitutes a "plausible" risk or a "significant contributor," are necessarily ambiguous. Others, such as thresholding at 10% or 25% of global population, are partly arbitrary (10% is intended as a marker for a precedented loss, and 25% is intended as an unprecedented decrease; see *SI Appendix* for further discussion). Further research is needed to sharpen these definitions. The thresholds for global catastrophic and decimation risks are intended as general heuristics and not concrete numerical boundaries. Other factors such as morbidity, and cultural and economic loss, need to be considered.

We define risk as the probability that exposure to climate change impacts and responses will result in adverse consequences for human or ecological systems. For the Climate Endgame agenda, we are particularly interested in catastrophic consequences. Any risk is composed of four determinants: hazard, exposure, vulnerability, and response (3).

We have set global warming of 3 °C or more by the end of the century as a marker for extreme climate change. This threshold is chosen for four reasons: Such a temperature rise well exceeds internationally agreed targets, all the IPCC "reasons for concern" in climate impacts are either "high" or "very high" risk between 2 °C and 3 °C, there are

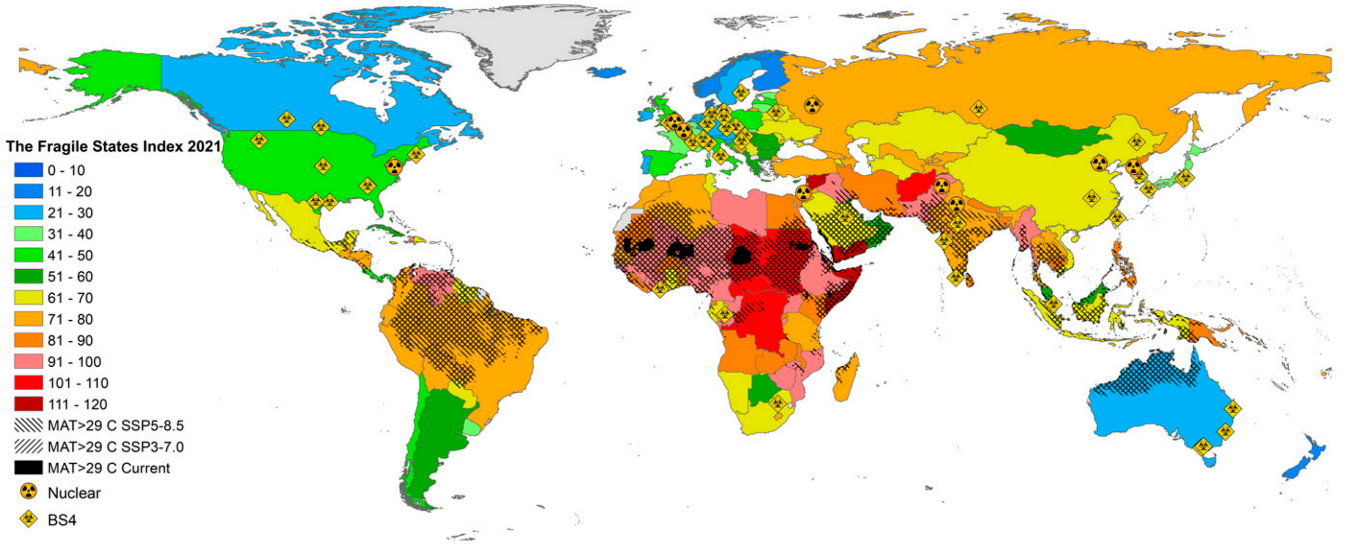

Fig. 2. Fragile heat: the overlap between state fragility, extreme heat, and nuclear and biological catastrophic hazards. GCM model data [from the WorldClim database (45)] was used to calculate mean annual warming rates under SSP3-7.0 and SSP5-8.5. This results in a temperature rise of 2.8 °C in ∼2070 (48) for SSP3-7.0, and 3.2 °C for SSP5-8.5. The shaded areas depict regions where MAT exceeds 29 °C. These projections are overlapped with the 2021 Fragile State Index (FSI) (49). This is a necessarily rough proxy because FSI only estimates current fragility levels. While such measurements of fragility and stability are contested and have limitations, the FSI provides one of the more robust indices. This Figure also identifies the capitals of states with nuclear weapons, and the location of maximum containment Biosafety Level 4 (BS4) laboratories which handle the most dangerous pathogens in the world. These are provided as one rough proxy for nuclear and biological catastrophc hazards.

Table 1. Defining key terms in the Climate Endgame agenda

Term	Definition
Latent risk	Risk that is dormant under one set of conditions but becomes active under another set of conditions.
Risk cascade	Chains of risk occurring when an adverse impact triggers a set of linked risks (3).
Systemic risk	The potential for individual disruptions or failures to cascade into a system-wide failure.
Extreme climate change	Mean global surface temperature rise of 3 °C or more above preindustrial levels by 2100.
Extinction risk	The probability of human extinction within a given timeframe.
Extinction threat	A plausible and significant contributor to total extinction risk.
Societal fragility	The potential for smaller damages to spiral into global catastrophic or extinction risk due to societal vulnerabilities, risk cascades, and maladaptive responses.
Societal collapse	Significant sociopolitical fragmentation and/or state failure along with the relatively rapid, enduring, and significant loss capital, and systems identity; this can lead to large-scale increases in mortality and morbidity.
Global catastrophic risk	The probability of a loss of 25% of the global population and the severe disruption of global critical systems (such as food) within a given timeframe (years or decades).
Global catastrophic threat	A plausible and significant contributor to global catastrophic risk; the potential for climate change to be a global catastrophic threat can be referred to as "catastrophic climate change".
Global decimation risk	The probability of a loss of 10% (or more) of global population and the severe disruption of global critical systems (such as food) within a given timeframe (years or decades).
Global decimation threat	A plausible and significant contributor to global decimation risk.
Endgame territory	Levels of global warming and societal fragility that are judged sufficiently probable to constitute climate change as an extinction threat.
Worst-case warming	The highest empirically and theoretically plausible level of global warming.

substantially heightened risks of self-amplifying changes that would make it impossible to limit warming to 3 °C, and these levels relate to far greater uncertainty in impacts.

Key Research Thus Far

The closest attempts to directly study or comprehensively address how climate change could lead to human extinction or global catastrophe have come through popular science books such as *The Uninhabitable Earth* (53) and *Our Final Warning* (10). The latter, a review of climate impacts at different degrees, concludes that a global temperature rise of 6 °C "imperils even the survival of humans as a species" (10).

We know that health risks worsen with rising temperatures (54). For example, there is already an increasing probability of multiple "breadbasket failures" (causing a food price shock) with higher temperatures (55). For the top four maize-producing regions (accounting for 87% of maize production), the likelihood of production losses greater than 10% jumps from 7% annually under a 2 °C temperature rise to 86% under 4 °C (56). The IPCC notes, in its Sixth Assessment Report, that 50 to 75% of the global population could be exposed to life-threatening climatic conditions by the end of the century due to extreme heat and humidity (6). *SI Appendix* provides further details on several key studies of extreme climate change.

The IPCC reports synthesize peer-reviewed literature regarding climate change, impacts and vulnerabilities, and mitigation. Despite identifying 15 tipping elements in biosphere, oceans, and cryosphere in the Working Group 1 contribution to the Sixth Assessment Report, many with irreversible thresholds, there were very few publications on catastrophic scenarios that could be assessed. The most notable coverage is the Working Group II "reasons for concern" syntheses that have been reported since 2001. These syntheses were designed to inform determination of what is "dangerous anthropogenic interference" with the climate system, that the UNFCCC aims to prevent. The five concerns are unique and threatened ecosystems, frequency and severity of extreme weather events, global distribution and balance of impacts, total economic and ecological impact, and irreversible, large-scale, abrupt transitions. Each IPCC assessment found greater risks occurring at lower increases in global mean temperatures. In the Sixth Assessment Report, all five concerns were listed as very high for temperatures of 1.2 °C to 4.5 °C. In contrast, only two were rated as very high at this temperature interval in the previous Assessment Report (6). All five concerns are now at "high" or "very high" for 2 °C to 3 °C of warming (57).

A Sample Research Agenda: Extreme Earth System States, Mass Mortality, Societal Fragility, and Integrated Climate Catastrophe Assessments

We suggest a research agenda for catastrophic climate change that focuses on four key strands:

- Understanding extreme climate change dynamics and impacts in the long term
- Exploring climate-triggered pathways to mass morbidity and mortality
- Investigating social fragility: vulnerabilities, risk cascades, and risk responses
- Synthesizing the research findings into "integrated catastrophe assessments"

Our proposed agenda learns from and builds on integrated assessment models that are being adapted to better assess large-scale harms. A range of tipping points have been assessed (58–60), with effects varying from a 10% chance of doubling the social cost of carbon (61) up to an eightfold increase in the optimal carbon price (60). This echoes earlier findings that welfare estimates depend on fat tail risks (31). Model assumptions such as discount rates, exogenous growth rates, risk preferences, and damage functions also strongly influence outcomes.

There are large, important aspects missing from these models that are highlighted in the research agenda: longer-term impacts under extreme climate change, pathways toward mass morbidity and mortality, and the risk cascades and systemic risks that extreme climate impacts could trigger. Progress in these areas would allow for more realistic models and damage functions and help provide direct estimates of casualties (62), a necessary moral noneconomic measure of climate risk. We urge the research community to develop integrated conceptual and semiquantitative models of climate catastrophes.

Finally, we invite other scholars to revise and improve upon this proposed agenda.

Extreme Earth System States. We need to understand potential long-term states of the Earth system under extreme climate change. This means mapping different "Hothouse Earth" scenarios (21) or other extreme scenarios, such as alternative circulation regimes or large, irreversible changes in ice cover and sea level. This research will require consideration of long-term climate dynamics and their impacts on other planetary-level processes. Research suggests that previous mass extinction events occurred due to threshold effects in the carbon cycle that we could cross this century (40, 63). Key impacts in previous mass extinctions, such as ocean hypoxia and anoxia, could also escalate in the longer term (40, 64).

Studying potential tipping points and irreversible "committed" changes of ecological and climate systems is essential. For instance, modeling of the Antarctic ice sheet suggests there are several tipping points that exhibit hysteresis (65). Irreversible loss of the West Antarctic ice sheet was found to be triggered at ∼2 °C global warming, and the current ice sheet configuration cannot be regained even if temperatures return to present-day levels. At a 6 °C to 9 °C rise in global temperature, slow, irreversible loss of the East Antarctic ice sheet and over 40 m of sea level rise equivalent could be triggered (65). Similar studies of areas such as the Greenland ice sheet, permafrost, and terrestrial vegetation would be helpful. Identifying all the potential Earth system tipping elements is crucial. This should include a consideration of wider planetary boundaries, such as biodiversity, that will influence tipping points (66), feedbacks beyond the climate system, and how tipping elements could cascade together (67).

Mass Morbidity and Mortality. There are many potential contributors to climate-induced morbidity and mortality, but the "four horsemen" of the climate change end game are likely to be famine and undernutrition, extreme weather events, conflict, and vector-borne diseases. These will be worsened by additional risks and impacts such as mortality from air pollution and sea level rise.

These pathways require further study. Empirical estimates of even direct fatalities from heat stress thus far in the United States are systematically underestimated (68). A review of the health and climate change literature from 1985 to 2013 (with a proxy review up to 2017) found that, of 2,143 papers, only 189 (9%) included a dedicated discussion of more-extreme health impacts or systemic risk (relating to migration, famine, or conflict) (69). Models also rarely include adaptive responses. Thus, the overall mortality estimates are uncertain.

How can potential mass morbidity and mortality be better accounted for? 1) Track compound hazards through bottom-up modeling of systems and vulnerabilities (70) and rigorously stress test preparedness (71). 2) Apply models to higher-temperature scenarios and longer timelines. 3) Integrate risk cascades and systemic risks (see the following section) into health risk assessments, such as by incorporating morbidity and mortality resulting from a climate-triggered food price shock.

Societal Fragility: Vulnerabilities, Risk Cascades, and Risk Responses. More-complex risk assessments are generally more realistic. The determinants of risk are not just hazards, vulnerabilities, and exposures, but also responses (3, 72). A complete risk assessment needs to consider climate impacts, differential exposure, systemic vulnerabilities, responses of societies and actors, and the knock-on effects across borders and sectors (73), potentially resulting in systemic crises. In the worst case(s), a domino effect or spiral could continuously worsen the initial risk.

Societal risk cascades could involve conflict, disease, political change, and economic crises. Climate change has a complicated relationship with conflict, including, possibly, as a risk factor (74) especially in areas with preexisting ethnic conflict (75). Climate change could affect the spread and transmission of infectious diseases, as well as the expansion and severity of different zoonotic infections (76), creating conditions for novel outbreaks and infections (6,77). Epidemics can, in turn, trigger cascading impacts, as in the case of COVID-19. Exposure to ecological stress and natural disasters are key determinants for the cultural "tightness" (strictness of rules, adherence to tradition, and severity of punishment) of societies (78). The literature on the median economic damages of climate change is profuse, but there is far less on financial tail risks, such as the possibility of global financial crises.

Past studies could be drawn upon to investigate societal risk. Relatively small, regional climate changes are linked to the transformation and even collapse of previous societies (79, 80). This could be due to declining resilience and the passing of tipping points in these societies. There is some evidence for critical slowing down in societies prior to their collapse (81, 82). However, care is needed in drawing lessons from premodern case studies. Prehistory and history should be studied to determine not just how past societies were affected by specific climate hazards but how those effects differ as societies change with respect to, for example, population density, wealth inequality, and governance regime. Such framing will allow past and current societies to be brought under a single system of analysis (37).

The characteristics and vulnerabilities of a modern globalized world where food and transport distribution systems can buffer against traumas will need to feature in work on societal sensitivity. Such large, interconnected systems bring their own sources of fragility, particularly if networks are relatively homogeneous, with a few dominant nodes highly connected to everyone else (83). Other important modern-day vulnerabilities include the rapid spread of misinformation and disinformation. These epistemic risks are serious concerns for public health crises (84) and have already hindered climate action. A high-level and simplified depiction of how risk cascades could unfold is provided in Fig. 3.

Integrated Catastrophic Assessments. Climate change will unfold in a world of changing ecosystems, geopolitics, and technology. Could we even see "warm wars"—technologically enhanced great power conflicts over dwindling carbon budgets, climate impacts, or SRM experiments? Such developments and scenarios need to be considered to build a full picture of climate dangers. Climate change could reinforce other interacting threats, including rising inequality, demographic stresses, misinformation, new destructive weapons, and the overshoot of other planetary boundaries (85). There are also natural shocks, such as solar flares and high-impact volcanic eruptions, that present possible deadly synchronicities (86). Exploring these is vital, and a range of "standardized catastrophic scenarios" would facilitate assessment.

Expert elicitation, systems mapping, and participatory scenarios provide promising ways of understanding such cascades (73). There are also existing research agendas for some of these areas that could be funded (87).

Integration can be approached in several ways. Metareviews and syntheses of research results can provide useful data for mapping the interactions between risks. This could be done through causal mapping, expert elicitation, and agent-based or systems dynamics modeling approaches. One recent study mapped the evidence base for relationships between climate change, food insecurity, and contributors to societal collapse (mortality, conflict, and emigration) based on 41 studies (88).

A particularly promising avenue is to repurpose existing complex models to study cascading risks. The resulting network could be "stress tested" with standardized catastrophic scenarios. This could help estimate which areas may incur critical shortages or disruptions, or drastic responses (such as food export bans). Complex models have been developed to help understand past large-scale systemic disasters, such as the 2007–2008 global financial crisis (89). Some of these could be repurposed for exploring the potential nature of a future global climate crisis.

Systems failure is unlikely to be globally simultaneous; it is more likely to begin regionally and then cascade up. Although the goal is to investigate catastrophic climate risk globally, incorporating knowledge of regional losses is indispensable.

The potentially catastrophic risks of climate change are difficult to quantify, even within models. Any of the above-mentioned modeling approaches should provide a greater understanding of the pathways of systemic risk, and rough probabilistic guides. Yet the results could provide the foundation for argumentation-based tools to assess the potential for catastrophic outcomes under different levels of temperature rise (90). These should be fed into open deliberative democratic methods that provide a fair, inclusive, and effective approach to decision-making (91). Such approaches could draw on decision-making tools under uncertainty, such as the minimax principle or

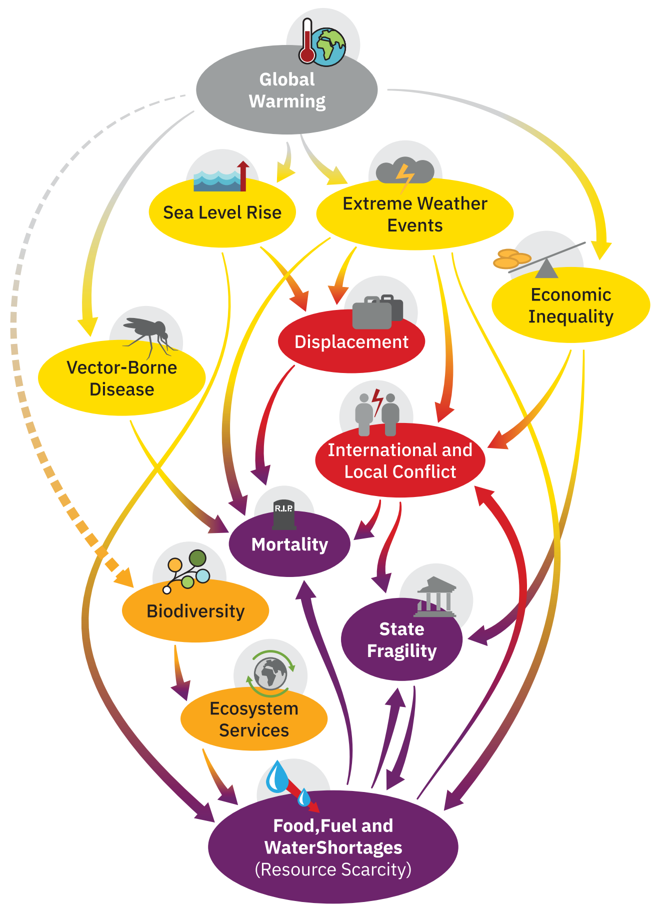

Fig. 3. Cascading global climate failure. This is a causal loop diagram, in which a complete line represents a positive polarity (e.g., amplifying feedback; not necessarily positive in a normative sense) and a dotted line denotes a negative polarity (meaning a dampening feedback). See *SI Appendix* for further information.

ranking decisions by the weighted sum of their best and worst outcomes, as suggested in the Dasgupta review of biodiversity (92).

An IPCC Special Report on Catastrophic Climate Change

The IPCC has yet to give focused attention to catastrophic climate change. Fourteen special reports have been published. None covered extreme or catastrophic climate change. A special report on "tipping points" was proposed for the seventh IPCC assessment cycle, and we suggest this could be broadened to consider all key aspects of catastrophic climate change. This appears warranted, following the IPCC's decision framework (93). Such a report could investigate how Earth system feedbacks could alter temperature trajectories, and whether these are irreversible.

A special report on catastrophic climate change could help trigger further research, just as the "Global warming of 1.5 °C" special report (94) did. That report also galvanized a groundswell of public concern about the severity of impacts at lower temperature ranges. The impact of a report on catastrophic climate change could be even more marked. It could help bring into focus how much is at stake in a worst-case scenario. Further research funding of catastrophic and worst-case climate change is critical.

Effective communication of research results will be key. While there is concern that fear-invoking messages may be unhelpful and induce paralysis (95), the evidence on hopeful vs. fearful messaging is mixed, even across metaanalyses (96, 97). The role of emotions is complex, and it is strategic to adjust messages for specific audiences (98). One recent review of the climate debate highlighted the importance of avoiding political bundling, selecting trusted messengers, and choosing effective frames (99). These kinds of considerations will be crucial in ensuring a useful and accurate civic discussion.

Conclusions

There is ample evidence that climate change could become catastrophic. We could enter such "endgames" at even modest levels of warming. Understanding extreme risks is important for robust decision-making, from preparation to consideration of emergency responses. This requires exploring not just higher temperature scenarios but also the potential for climate change impacts to contribute to systemic risk and other cascades. We suggest that it is time to seriously scrutinize the best way to expand our research horizons to cover this field. The proposed "Climate Endgame" research agenda provides one way to navigate this under-studied area. Facing a future of accelerating climate change while blind to worst-case scenarios is naive risk management at best and fatally foolish at worst.

Data Availability. Previously published data were used for this work (45, 46, 48, 49).

ACKNOWLEDGMENTS. We thank Benedikt Knüsel, Mark Lynas, John Broome, Ingo Fetzer, Peter Watson, Florian Ulrich Jehn, Zoe Cremer, Constantin Arnscheidt, Nathaniel Cooke, two anonymous reviewers, and the PNAS editor for their helpful comments. We thank Dirk Biermann, Janin Schaffer, and Killian Cremer for their assistance with Fig. 3.

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