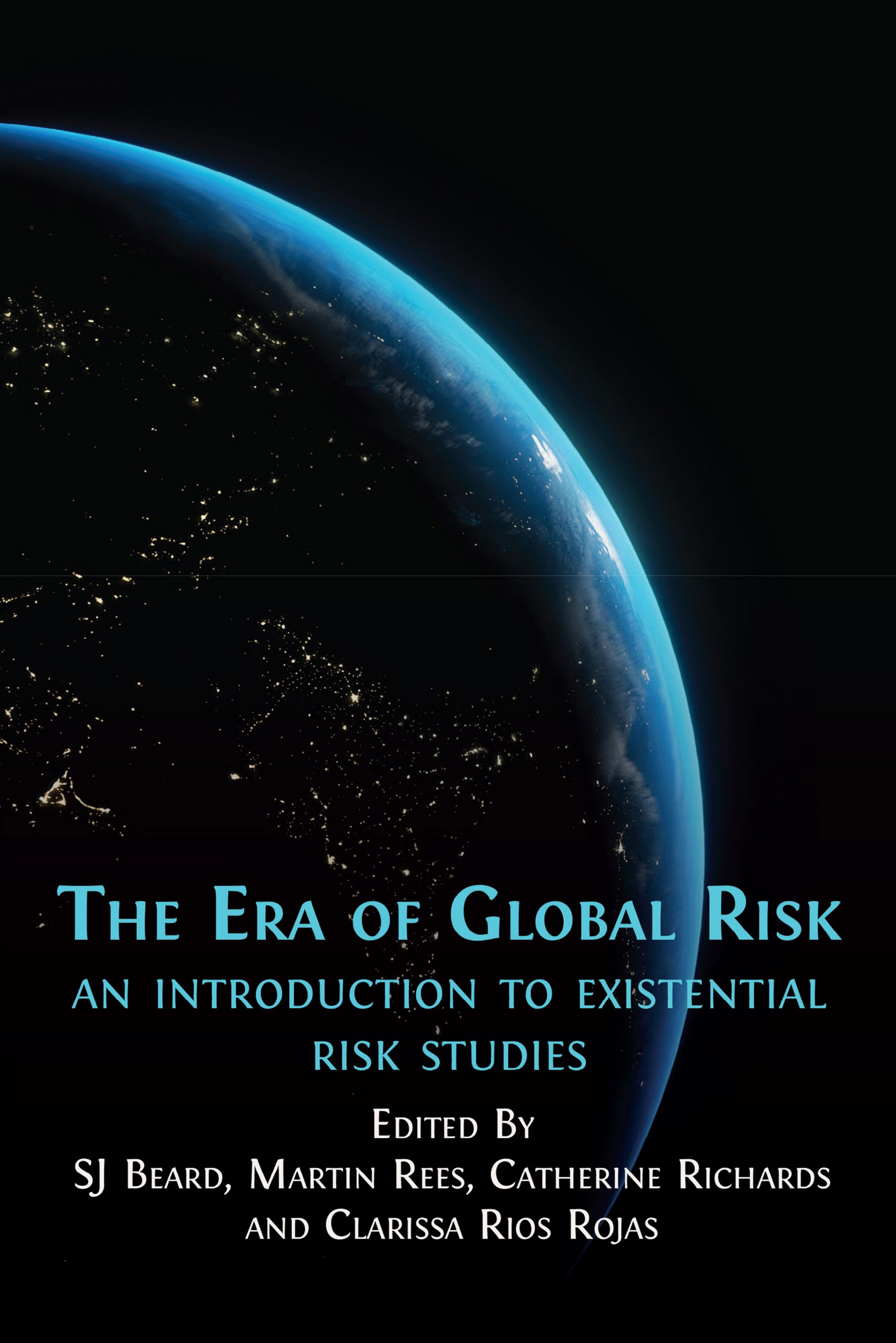

The Era of Global Risk

An Introduction to Existential Risk Studies

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7. Ecological Breakdown and Human Extinction

Luke Kemp[1]

In 1988 the Toronto Conference declaration described climate risks as "second only to a global nuclear war". The latest estimates suggest that a full-scale nuclear war could result in casualties of more than five billion.[2] Could climate change be this calamitous or even worse? What about when we consider the full range of ecological threats we face? In short, could global ecological collapse cause human extinction?

In this chapter, we will explore this question by examining how the science of ecological crisis has progressed over the past decades, what it means for the likelihood of human extinction, and whether we have cause for optimism. Along the way, we will also discuss why the existing definitions of 'existential' are not useful for assessments of catastrophic risk, and why the common question "Is climate change an existential threat?" is not sensible.

Our focus will largely be on climate change. This is because it is the most well-researched and visible contributor to global ecological risk. Yet, it cannot be easily disentangled from our other planetary boundaries. This analysis should be seen as a partial and likely conservative overview. For this chapter I will use the definitions for terms such as catastrophic and existential risk that are outlined in our previous paper Climate Endgame.

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The state of the science

Uncertainty, tail-risks, and tipping points

For many ecological risks, it appears that the more we know, the worse the threats appear.

For climate change, the best indication for this is a change in the 'reasons for concern' across consecutive IPCC assessment reports. The IPCC identifies five 'reasons for concern': 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. These are intended to be indicators to inform the world of how close we are to "dangerous anthropogenic interference with the climate system", the central mission of international climate policy.[3] These reasons for concern are determined by IPCC authors as a reflection of expert opinion, and underpin the famous 'burning embers' diagram. The diagram shows, in a thermostat fashion, at what temperature the risk of these different concerns is. Over time, with each successive report, the risk levels for any given temperature have risen. That is, these reasons for concern have become more worrisome, even at lower temperatures, as the science has progressed.[4] In the fifth Assessment Report (AR5), all of the reasons for concern were 'high' or 'very high' likelihood for just 2–3°C of warming.[5]

Tipping elements in the Earth System have followed the same trend as the reasons for concern. That is, over time the likelihood of crossing tipping points at low levels of warming has been rising. Tipping elements refer to when warming breaches a critical threshold, causing a change in one part of the climate system to become self-perpetuating, resulting in potentially significant Earth System impacts. This includes Artic Winter Sea ice collapse and dieback of the Amazon Rainforest. The most recent assessment of evidence on tipping elements found that out of 16 tipping elements, six are at a high likelihood of being tipped at 1.5–2°C of global heating. This includes events such as the die-off of low-latitude coral reefs, as well as the long-term collapse of the West Antarctic and Greenland Ice Sheets. Hence, even the ambitious goal of limiting warming to 1.5°C above pre-industrial temperatures would likely activate multiple tipping elements.[6]

The study of tipping points and regime shifts in ecosystems has progressed significantly, leading to new insights.[7] We now have nascent findings suggesting that such radical changes often occur in a domino effect.[8] For climate change, this has been termed a 'tipping cascade'.[9] Moreover, it appears that the larger and more complex the ecosystem, the more rapid and complete its potential collapse.[10] Such lessons are not causes for comfort.

There is more mixed news on equilibrium climate sensitivity. Climate sensitivity refers to the response of the climate system to a doubling of greenhouse gas concentrations. Since approximately the 1970s and 80s, such a response has been estimated to be between 1.5–4.5°C—that is, until the most recent sixth Assessment Report (AR6) of the IPCC. AR6 reports a narrower likely range (66–100%) of 2.5–4°C and very likely range (90–100%) of 2–5°C. The upside of this is that high sensitivities of >4°C are less likely than previously expected. The downside is that the IPCC is now 'virtually certain' (99–100%) that climate sensitivity will be above 1.5°C, since all lines of evidence run strongly against these lower levels of warming.[11] Unfortunately, a climate sensitivity of greater than 4.5°C, while unlikely, could not be ruled out as lower levels have been. These findings echo a major study on climate sensitivity in 2020, which used a Bayesian approach with multiple strands of evidence.[12]

These new findings imply that a doubling of greenhouse gas concentration (which could occur this century) would run an 18% chance of causing 4.5°C or more of warming. This echoes earlier estimates of surprisingly high likelihoods of disturbingly high temperatures. Wagner and Weitzman estimate that under a concentration of 700 parts per million (ppm) (which falls within a mid-high scenario),[13] there is an approximately 10% chance of exceeding 6°C by the end of the century (note that this would be slightly lower under the latest ECS estimates).[14] Temperatures this high last occurred 50 million years ago and have never been experienced by hominids.[15] Such rapid warming is geologically unprecedented, and a rise that is an order of magnitude faster than what occurred during the worst mass extinction event: the End-Permian Extinction.

In the slightly longer term, even more radical pulses in heat may be possible. One basic model found that stratocumulus cloud decks may abruptly be lost, causing ~8°C global warming, with CO^2 concentrations that could be approached by the end of the century.[16] This 8°C would be additional to the previous level of warming needed to trigger this tipping point. Other studies have shown the potential for strong cloud feedbacks to push rapid and irreversible warming.[17]

Over the past decades, knowledge of catastrophic climate change has risen alongside—but not kept pace with—global emissions. Unfortunately, the higher-end warming scenarios that matter the most are those we know least about. One recent study, text-mining IPCC reports, found that there was a significant mismatch between coverage of different levels of warming and their likelihood. Similarly, a recent survey by *Nature* of 234 IPCC authors found that over 60% of people surveyed expected warming of 3°C or above by the end of century.[18] However, in existing assessment reports, less than 10% of the mentions of temperature rise refer to 3°C or above.[19] IPCC reports have given disproportionate attention to lower temperature scenarios (2°C or lower) relative to their likelihood and impact. This trend is increasing over time, with each subsequent Assessment Report covering extreme temperature rise less.[20] Indeed, the IPCC notes in its 2014 Fifth Assessment Report that there have been few quantitative investigations of the global impacts of warming above 3°C.[21] Regardless of their likelihood, the higher impact of these scenarios makes them even more vital to robust decision-making under uncertainty. The gap between likely scenarios and our knowledge is disconcerting.

One of the glimmers of hope over past decades has been some limited progress in emission reductions. The falling prices and increasing deployment of renewable energy has made the worst-case emissions scenario (previously RCP8.5, now SSP5–8.5) increasingly unlikely.[22] This should not be grounds for complacency. High temperatures and extreme impacts can still be reached even with lower anthropogenic emissions. That is because emissions concentrations are reflective not just of human emissions, but also the reaction of the Earth System. Moreover, there is still substantial uncertainty over greenhouse gas trajectories. Cumulative emissions to date have most closely tracked the RCP8.5 scenario.[23] Long-run changes in technology, energy demand, and economic growth are all highly uncertain and will have a significant impact on how much carbon is released. One study using an expert survey and econometric modelling found that annual economic growth rates of 2.1% (with a standard deviation of 1.1%) over the next century were plausible. These high growth rates yield a >35% likelihood that emissions would exceed the RCP8.5 pathway.[24] Moreover, even the best super-forecasters of geopolitical events cannot make accurate predictions for events over a year away.[25] We need to maintain a healthy skepticism over our ability predict what the world's geopolitical and energy systems—and, hence, our emissions—will look like in a century.

Despite some improvements, the overall emissions picture remains dire. Assuming full implementation of the climate pledges under the Paris Agreement (nationally determined contributions, or NDCs), emissions will have increased by 13.7% in 2030 relative to 2010.[26] One of the least discussed and most important obstacles is the reality of delay. Previous studies have found that the delay in undertaking emissions reductions is the largest influence on the costs and likelihood of meeting a given target.[27] This is an 'emerging consensus' across climate economics.[28] The main impediment is the lock-in of fossil-fuel-intensive infrastructure. Delay to date has been primarily due to one key factor: the fossil-fuel industry and the wealthy who benefit from a fossil-based economy.

We should be careful not to tie climate risk solely to the level of warming. Under the right conditions, climate change could have catastrophic impacts, even at just 2°C of warming.[29] When thinking through extreme climate risk, we need to consider not just emissions and the associated level of warming, but also the impacts, social vulnerability to these impacts, and the response of domestic and international communities.[30]

Complex ends: Cascading crises and risks

Extinction is complicated. Each of the five mass extinction events throughout the phanerozoic history of Earth has involved a complex of different factors including oxygenation, volcanic eruptions, asteroid strikes, and food web cascades. One of the few common imprints is climatic change. Global warming likely played a central role in each mass extinction event, perhaps even the Late Ordovician (previously assumed to be a cooling event).[31] Fast-forward to human history: while we have no account of Homo sapiens going extinct, we do have a record of states, empires, and kingdoms crumbling,[32] as well as the extinction of other hominid species.[33] It is always a confluence of vulnerabilities, exposures, responses, and hazards—and one that frequently has the fingerprint of climatic change.[34]

The science of climate change and other global ecological threats has progressed considerably since 2004. Perhaps the greatest shift in the field has been away from thinking about a list of individual ecological hazards, towards thinking about how systems transform and fail. We are slowly realising that, like mass extinction events and societal collapses, ecological catastrophe will not be a simple affair. Instead, these 'Anthropocene risks' involve human-driven processes that interact with interconnected global socio-ecological processes and have complex, cross-scale relationships. The study of such risks necessitates a new approach to governance that includes an appreciation of justice, inequality, and the agents driving us towards disaster.[35]

Global ecological threats are increasingly thought of as a study of complex systems. Earth Systems science is evolving as a discipline and is increasingly thought of as a set of interconnected 'planetary boundaries'.[36] Climate is only one of these boundaries and is accompanied by stratospheric ozone depletion, biosphere integrity, novel entities, ocean acidification, freshwater use, land system change, biochemical flows, and atmospheric aerosol loading. Each boundary is linked to a different planetary sub-system that could be pushed into instability by human pressures. The study of regime shifts in smaller ecosystems—such as pollinator communities,[37] and coral reefs[38]—takes a similar approach.

These are matters of systemic risk:[39] systems can change rapidly into a new state (like a vibrant coral reef transforming into an algae-dominated environment) based not just on single hazards, but the structure of the system, internal feedbacks, and sets of interacting stressors. This systemic view is not just restricted to ecology, but has also become commonplace in studying financial crashes and societal crises more broadly.[40] Such a lens has not only highlighted concern over potential 'tipping points' in the Earth System,[41] but also the chance of irreversible changes. For instance, relatively small levels of warming locking the world into far higher temperatures and a 'Hothouse Earth' trajectory.[42] Similarly, irreversible loss of the West Antarctic ice sheet will likely occur at approximately 2°C and the current ice configuration will not be regained even if we lower temperatures back to present levels.

Risk comes not just from the potential changes in the Earth, but also from human responses. The IPCC, in its sixth assessment report, has explicitly recognised this, defining risk not only in terms of impact, but also responses. This is a new, state-of-the-art complex risk assessment: a consideration of hazards, vulnerabilities, exposures, and responses.[43] Alongside these determinants of risk, we need to better understand how risks could cascade, including across sectors, countries, and even systems.

The most obvious and dramatic example of a response risk is geoengineering: large-scale interventions into the Earth System to mitigate the effects of climate change. Carbon dioxide removal (or 'negative' emissions) through direct air capture of greenhouse gases, afforestation, or reforestation would be the lowest risk option, but appears unlikely. It would require a herculean effort to develop and deploy the technologies and infrastructure needed for large-scale negative emissions within decades.

Instead, the lowest-cost and most likely option is also the riskiest: stratospheric aerosol injection (SAI). SAI involves injecting particles into the atmosphere to reflect sunlight. One recent risk assessment of SAI suggested that the largest threat comes from 'latent risk': abrupt warming that would accompany the deactivation of the SAI system. Currently there are no clear mechanisms for the direct ecological impacts to be catastrophic, although these cannot be ruled out due to the nature of the Earth System. SAI would provide several stressors to the global system, including through changing disease patterns and precipitation, as well as the potential for political conflict, but these are all understudied. The largest contributor to risk from SAI is that another catastrophe—whether it be nuclear war, a solar flare, or mass pandemic—would knock out the system, leading to warming that would otherwise takes decades, rushing in within years. Hence, SAI shifts the risk distribution. The median-case scenarios are potentially less severe than the impacts of climate change. But the worst case is intensified. SAI, if it is used to cover significant amounts of warming, would constitute a planetary sword of Damocles.[44]

Large amounts of warming and monumental Earth-engineering may not be needed to trigger catastrophe. Historically, minor climatic perturbations and droughts appear to have contributed to the dissolution of dozens of empires and kingdoms, ranging from the Bronze Age world system to the Khmer Empire, Western Roman Empire, and Assyrian Empire.[45] Yet many proved resilient to similar stresses. For instance, the Mayan city-state of Caracol experienced two similar droughts during its lifespan, one of which it navigated with few signs of breakdown, and the other which coincided with a rapid and enduring crisis. The largest difference appears not to be the severity of the drought, but that Caracol was riven by warfare and inequality when it hit the second time.[46]

Risk cascades still largely exist under a fog of uncertainty. Studies currently suggest that climate change can worsen and trigger conflicts under conditions such as weak governance and ethnic divisions,[47] although we do not know how this relationship could morph under higher temperatures. Similarly, temperature does seem to have an innate and often non-linear relationship with economic growth[48] and even population spread and density. It has been suggested that humans, much like other species, have a fundamental climatic niche—that is, a specific climate envelope of approximately 13°C (mean annual average temperature) that the majority of human population and urban areas have developed within over millennia.[49] Perhaps the best study to date on risk cascades and feedbacks used 41 studies to empirically sketch the links between climate change, food insecurity, and societal collapse (population loss through conflict, mortality, and emigration).[50] Other researchers in global catastrophic risk have also begun putting forward frameworks for more complex risk assessments,[51] including for climate change[52] and international governance.[53] For now, far greater attention and research is needed on these systemic effects, such as climate triggering conflict, political change, or even financial crises.

Indeed, understanding 'societal fragility' is a key part of the Climate Endgame research agenda, alongside exploring long-term extreme Earth System states, modelling mass mortality and morbidity, and undertaking integrated climate catastrophe assessments, which include climate change alongside a host of other catastrophic threats and vulnerabilities.[30]

An existential end?

Could global environmental collapse cause human extinction?

This leads us to the central question: could combined ecological crises cause this to be humanity's final century? Few have been bold enough to directly broach the question. There have been many prophesied warnings, especially within the collapse literature, but no truly comprehensive scientific assessments. Questions of catastrophe are not directly addressed by any relevant, international scientific institutions, such as the Intergovernmental Panel on Climate Change (IPCC) or Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES).

Many individual papers have mentioned the catastrophic potential of climate change. Peer-reviewed academic studies have referred to global warming as an "existential threat",[5] "beyond catastrophic" (for above 5°C),[54] and "an indisputable global catastrophe" (for above 6°C).[55] While the impacts of climate change alone seem capable of causing a global catastrophic risk, the authors never spell out how the world would fall from such impacts to mass mortality. Importantly, the gloomy terms are never defined, leaving it unknown as to whether the authors believe that certain levels of warming could plausibly lead to human extinction. These are no studies nor proofs of existential risks from climate change, but rather indications of a lack of shared terminology.

In lieu of sustained scientific attention, the most poignant examinations have come from popular books. Mark Lynas in *Our Final Warning* concludes, based on a large-scale review of the existing scientific literature, that 4°C could threaten a global collapse, and 5–6+°C could unravel into human extinction.[56] David Wallace-Wells in *The Uninhabitable Earth* guesses that, in contrast to the title, the Earth will not become uninhabitable, and humans will survive foreseeable levels of warming.[57] Toby Ord in *The Precipice* suggests a 1 in 1000 chance of climate change resulting in an existential catastrophe.[58] William MacAskill in *What We Owe the Future* suggests that "it's hard to see how even this could lead directly to civilizational collapse".[59]

The assessments by existential risk scholars—Ord and MacAskill—have been the least convincing thus far. Ord uses an unworkable, ambiguous definition of existential risk.[60] He defines an existential risk as one that "threatens the destruction of humanity's longterm potential". However, what our potential is depends on one's values. Ord suggests that we minimise existential risks first and then determine "our potential" through a "Long Reflection". This would essentially be a centuries-long worldwide philosophical conversation. This strategy creates a paradox: we are supposed to minimise risks to a concept that we cannot define until after we have reduced those risks. It is difficult—if not impossible—to assess climate change using this definition, as Ord doesn't explicitly state his values, nor what "our potential" is. His analysis misses much of the most recent science and does not sufficiently consider 'indirect' impacts. Moreover, the chapter does not cogently answer the question of whether climate change will result in human extinction. Instead, after roughly estimating the direct impacts, Ord concludes that they will not make the entirety of Earth uninhabitable. This is an entirely different question to the likelihood of climate change causing human extinction. Ord's use of a precise numerical figure is also largely baseless. As noted earlier, even groups of the best super-forecasters making predictions on clearly defined questions have little accuracy after 12 months.[61]

MacAskill's analysis is also riddled with problems. Like Ord, he suffers from definitional problems. He defines 'civilisational collapse' as society losing the ability to create most industrial and post-industrial technologies.[62] This has little relation to more common definitions of societal collapse. It also assumes that we know the full range of potential industrial and post-industrial technologies. Worse still, like with Ord's analysis, it replaces the question of whether climate change will cause civilisational collapse with an easier one: will climate change make large-scale agriculture on Earth impossible? MacAskill concludes no. Once again, this is a different question. In short, the coverage of climate change by the most prominent existential risk scholars has been simplistic and disappointing.

While brave, the conclusions of Wallace-Wells and Lynas are ultimately individual guesses with multiple shortcomings. Wallace-Wells is unclear about how he reaches his conclusion. Lynas relies on geological studies and the analogous example of the End-Permian Extinction. His more pessimistic assessment appears the most compelling. It has the most thorough grounding in the literature and, in the face of deep uncertainty, relies on the most reliable and relevant geological precedents.

This is astute, given that studies suggest that mass extinction events work by a threshold effect for temperature or carbon that we look likely to exceed. One analysis from 2021 found that warming of 5.2°C would likely result in a mass extinction event, even without considering the other anthropogenic impacts on the Earth.[63] Another study suggested that the threshold for carbon release to result in a mass extinction event would be crossed by most IPCC scenarios by the end of the century (assuming a 50% uncertainty range, we may have already crossed this precipice).[64]

Yet, these investigations suffer from the same problem, one that plagues the entire study of global catastrophe and human extinction: a lack of proven or reasonable tools and methods for discerning when a crisis could spiral into global calamity. Few attempts have been made, with the notable exception of the societal collapse and climate review conducted by Richards et al., which does attempt to cautiously trace out some pathways from impacts to conflict and mass mortality.[65] Notably, these deal only with climate change and not the broader, reinforcing web of ecological crises, which has received less attention.

The short answer is that we do not know whether climate change or anthropogenic ecological disruption could spiral into human extinction. However, this is true for all the suspected causes of human extinction. Climate and ecological crises do appear to have one of the most concerning profiles, given their range of impacts, as well as their role in past mass-extinction events and periods of historical turmoil. There are enough reasons to take this question of human extinction from ecological breakdown seriously.

For now, while uncertainty remains, it seems improbable that human actions could extinguish the biosphere. Another mass-extinction event is plausible, but complete annihilation of the biological realm is likely not. Barring science fiction, the only semi-plausible direct route for human activities to terminate all biological life is the triggering of a runaway greenhouse effect. Lynas has suggested that such a scenario is possible, if there are hidden, extreme positive feedback loops in the climate system, an enormous, profligate use of fossil fuels, and increasing solar radiation.[66] Some basic modelling of the climate system has suggested that a runaway greenhouse effect is plausible.[67] This is further supported by recent modelling of potential cloud feedbacks leading to a moist greenhouse.[68] However, these studies are based on high-level models with many assumptions.

The current scientific consensus is that any hellish mechanism—which could lead to a furnace Earth, complete with evaporated oceans—is highly unlikely. In 2009, the IPCC reported, in its 31st meeting, that a "runaway greenhouse effect" analogous to Venus appears to have virtually no chance of being induced by anthropogenic activities.[69] Whether this view continues to hold, given the new modelling outcomes, is unclear. For now, while extinguishing the entire web of life seems far less likely than causing human extinction, it is an outcome that cannot be entirely ruled out.

If humans were to go extinct, it is likely that global ecological collapse would be one of a series of drivers. Imagine a world where, in 2075, we have reached 4°C of warming. The climate system was more sensitive than expected, and new energy-hungry machine learning algorithms led to higher-than-expected energy demand. After a category 6 hurricane hits New York City, NATO (led by the US) deploys a global stratospheric aerosol injection (SAI) system. This enflames international tensions and stokes domestic unrest in societies already awash with disinformation driven by deep-fakes and other high-level machine learning applications. A nuclear war breaks out and the ensuing nuclear winter knocks out the SAI system. The few billion survivors emerge from nuclear winter to be faced by soaring temperatures as the Earth warms by 4.5°C in the space of decades. Sources of sustenance beyond agriculture, such as marine fish stocks, have been significantly affected by transgressing other planetary boundaries such as ocean acidification, biosphere integrity, and biogeochemical flows. The rapid changes in temperature cause significant changes in wildlife distribution, triggering new zoonotic pandemics. Simultaneously, the unplanned emergency evacuation of one biosafety level 4 (BS4) facility just prior to the nuclear conflict led to the release of a modified version of the previously defeated smallpox virus. The survivors are ingenious and resilient but fail to recapture the right industrial technologies required to put an SAI system back online. Many have intentionally turned away from industrial technologies after the fall. Those that try are faced with the problem of energy return on investment: easily accessed fossil-fuel reserves have already been depleted and the leftovers are too costly to use at scale. After a long fight, the final sapien takes her last breath. She is a Māori woman, living on the outskirts of modern-day Dunedin (New Zealand). Her body, riddled with the scars of an altered smallpox strain and signs of malnourishment, finally gives out. Humanity is extinguished.

This is one speculative and indicative example of an extinction scenario. Yet it touches on an important point. That is, asking the question of 'is climate change or ecological breakdown an existential risk?' is ultimately simplistically misleading. No single hazard is an existential risk. In the scenario outlined above, a global society marked by high levels of equality, international cooperation, and adaptive technology could have potentially weathered the same ecological conditions. Whether our combined global environmental crises could spiral into extinction depends on human responses and wider trends and vulnerabilities (such as inequality). Climate change and planetary boundaries challenge the traditional, simplistic approach of thinking of existential risk as a simple set of disconnected hazards. Indeed, no single hazard is likely to result directly in human extinction. The search for one single event to kill us all will lead us to science fiction.[70] We should instead think of the overall level of risk that arises from any particular socio-economic system (such as the current fossil-fuel-driven, globalised, capitalist economy). Answering the question of whether climate change is an existential risk is a futile inquiry until we develop reasonable definitions of existential risk, a topic we turn to next.

Limits to growth as an existential saviour and threat

Can we grow into catastrophe, collapse, or even human extinction?

There is a rising scholarly debate over whether continued economic growth is compatible with living on Earth—or even desirable. This debate dates back to at least the 1970s with the publication of the Club of Rome's *Limits to Growth* report.[71] The report relied on a computer-based systems model, which was (at the time) state-of-the-art. The model attempted the ambitious task of modelling the global economy. Repeated runs of the model led to a chilling observation: any simulation with continued, unabated population and economic growth eventually led to a global collapse in industrial output and population. A study conducted some 30 years later ran the model again with updated data, finding that it fitted trends over the last three decades remarkably well.[72]

The *Limits to Growth* thesis has been a source of heated debate. Proponents of the 'degrowth' approach argue that, to date, no country has decoupled material consumption from economic growth,[73] that limiting warming to 1.5°C or 2°C will require contractions in energy demand (and likely economic activity) which are incredibly challenging to achieve alongside continued economic growth, that infinite growth is impossible on a finite planet,[74] and that growth brings neither happiness nor human flourishing.[75] Critics argue that degrowth —even if combined with redistribution—will condemn the world to low living standards,[76] that absolute decoupling between emissions and economic activity is already proving possible,[77] and that the limits to growth will lie well beyond Earth due to the inexhaustible resource of human ingenuity. The debate is likely unresolvable: no amount of empirical evidence can falsify the potential power of future innovation and invention. Similarly, no amount of evidence can verify the *Limits to Growth* trajectory until we are amidst a collapse.

Strangely, even if the notion of *Limits to Growth* is incorrect, the very idea of it could be an existential risk according to the traditional definition. This is due to the traditional definition being odd and idiosyncratic. The canonical definition of existential risk labels it as a risk that will "annihilate Earth-originating intelligent life or permanently and drastically curtail its potential".[78] The definition was later refined and specified to mean any threat that prevents the stable attainment of 'technological maturity'[79]—that being the maximum, feasible control over the environment (including the entire universe) and level of economic productivity. Technological maturity is not usually envisioned as an Earth-bound enterprise, but an endeavour of space colonisation by a post-human species.[80] Thus, an existential risk is anything that threatens this techno-utopian future, including a technological or economic plateau.

Under this classical definition, the idea of *Limits to Growth* is an existential risk: if it is correct then continued growth trends could result in catastrophe, as indicated by the modelling study. Yet, regardless of whether the thesis is true or not, if we act to limit human activities and stay within planetary boundaries, we would also face an existential risk under the canonical definition by not reaching a techno-utopian future. This says much more about the flaws and problems of these definitions of existential risk than it does about the desirability of limiting economic growth or the validity of the limits to growth idea.

If we are going to have a mature, scientific field then we need better definitions. We should start by splitting out questions of existential ethics (what humanity's potential is, and the value of different long-term futures) and extinction ethics (the goodness or badness of human extinction) from the study of global catastrophic and extinction risk.[81] Existential risk cannot be tied to one idiosyncratic view of the future nor such vagaries as 'our potential'. We also need to have a more refined concept of risk. Risk is not a single hazard like a biologically engineered pandemic. It is the likelihood of an adverse outcome, given exposure to certain conditions. For instance, we should think of extinction risk as the overall likelihood of humans going extinct in a particular period, and extinction threats as major contributors to this overall level of risk. The 2022 *Climate Endgame* paper puts forward a set of definitions reflecting this way of thinking, and a suggested full spectrum of calamity from global decimation risk through to human extinction.[30]

Hope in the heat: Responsibility and responses

Responsibility: Tragedy of the elite, not the public

The responsibility for most ecological crises is concentrated. From the lens of national emissions, just ten historical emitters account for over 75% of cumulative international emissions.[82] For extraction, just six countries and one region of 18 countries account for over three quarters of fossil-fuel reserve.[83] Similarly, there is growing evidence that material consumption and consumption norms for wider society are driven by a narrow supper-affluent elite.[84] The influence of the wealthiest is not just in norms, but also direct carbon inequality. Recent research from Oxfam suggests that the richest 1% of individuals globally emit more than double that of the poorest half of humanity. From 1990–2015, the cumulative emissions share of the richest 1% and 10% of the world were 15% and 52% respectively. The skewed distribution for responsibility exists in areas outside of emissions.[85] One recent analysis suggests that the corporate financing of the deforestation of the Amazonian Basin is enabled by a handful of key investment firms.[86]

The lack of policy responses is also a concentrated affair. For climate change, a collection of organisations and individuals funded by the fossil-fuel industry has deliberately undermined public trust in climate science and strangled the policy response. For decades, the fossil-fuel industry has funded scientists and firms—and even set up fake community groups—to muddy the science of climate change. These are the well-funded and well-documented 'Merchants of Doubt'.[87] This was combined with the suppression of in-house climate research from several fossil-fuel giants.[88] Through other actions, such as lobbying and political subterfuge, the fossil-fuel industry has played a central role in delaying and distorting efforts to reduce emissions over the past three decades.[89] Exxon, through the International Petroleum Industry Environmental Conservation Association (IPIECA), has coordinated efforts across the industry to both discredit the science and stop international climate policy since the 1980s.[90] Neither emissions nor the lack of a policy response can be easily tied to the global public. The idea that 'we are all to blame' was, instead, part of an intentional rhetorical strategy from ExxonMobil and others to shift responsibility to consumers.[91] The threat is not humanity writ large. Rather, it is from a small, powerful band who overwhelmingly profit from the global machinery of extraction. It is largely a matter of public risks and private benefits.

Why is responsibility important? Does identifying, or targeting, the culprits behind ecological devastation bring us closer to solutions? Yes, of course it does. Across different risks and risk determinants (hazards, vulnerabilities, exposures, and responses), there are often common drivers.[92] Striking these common roots is a far more effective long-term solution than attempting to grapple with the symptoms. This is not just true for climate change. For all anthropogenic catastrophic hazards, the responsibility is concentrated, and the powerful producers (the 'Agents of Doom') of these threats have played a starring role in thwarting societal responses.[93] Ironically, these actors also tend to disproportionately benefit from the execution of emergency powers during crises.[94] Addressing risk will ultimately mean dealing with and curtailing the political power of these actors. This should be a source of hope. The concentrated nature of responsibility means interventions should be easier to target and implement. It also means that reducing catastrophic risks could have the co-benefit of creating a more equal world.

The co-benefits of avoiding global ecological catastrophe

Global catastrophe is rarely a matter for optimism. For anthropogenic hazards, such as advanced algorithmic systems and synthetic biology, the hyped benefits are disconnected from their risk mitigation. They are dual use, and a common view is that we will either self-capitulate with them or achieve technological salvation. However, there may be many co-benefits from not developing certain technologies. For example, avoiding the rapid development and deployment of AI systems would not just avert fears overreaching unaligned superintelligence, but also nearer-term concerns over surveillance and disinformation. However, this is rarely discussed and is usually dismissed as being impossible or not worth the loss of the potentially beneficial applications.

Ecological risks represent a different matter altogether. They are an area where risk mitigation does not just involve building a safer world, but also one with greater welfare and health. This is the increasingly convincing story told by the 'co-benefits' literature. It is an area of study that has swelled since the publication of *Our Final Century*. The message from most studies is that the mitigation of environmental problems—most notably climate change—yields many benefits, including improved health, economic performance, employment, and energy security.[95] Once these benefits are accounted for, the economics fundamentally shift: avoiding climate change is likely to result in net economic benefit, regardless of the warming averted. The same calculus applies to ecosystem services. Estimates of global ecosystem services place their value at equal to or greater than double global GDP—for instance, approximately $125 trillion in 2011,[96] a finding that should be entirely unsurprising given that all economic activity is dependent on a functioning Earth System.

Most actions to cut emissions are 'no-regrets' options. This is uncontroversial and well known for measures such as energy efficiency.[97] What is less widely known, but increasingly clear, is that this holds for a much greater suite of actions, including vehicle electrification and renewable energy. Overall, decarbonisation already appears cheap, and the projected costs tend to fall with each new assessment due to the plummeting price of renewable energy.[98] When the co-benefits and co-harms are included in an economic analysis, then optimal climate policy—which could be compatible with 2°C or 1.5°C, depending on our risk adversity and how we value human health—becomes an automatic net benefit.[99] There are other potential trade-offs that we must be cognisant of, including the loss of marginalised workers in the fossil-fuel sector, disproportionate impacts on indigenous communities for resource extraction, and the potential for resource exhaustion. This has led to calls for a just transition.[100] This is an admirable and necessary approach. Nonetheless, the potential downsides of decarbonisation are still far less disturbing and costly than fossil-fuel extraction.

The net benefit of mitigation is largely due to the dark, externalised costs of fossil fuels, most notably on human health. According to one estimate, in 2012, particulate matter from the combustion of fossil fuels caused approximately 10.2 million excess deaths. In 2018, such deaths account for approximately 18% of global deaths.[101] This is only mortality. The cost is even higher when lost productivity and sickness are considered. These overall health costs are enormous. Even in the US, the health costs of coal-fired power are likely 0.8–5.6 times the value added to the economy.[102] Globally, the health effects of fossil fuels could justify a carbon price of $50–380.[103]

There are also a range of other potential advantages that are rarely included in naïve cost-benefit calculations. Chief among these is avoiding the geopolitical quagmire caused by fossil-fuel supply. Securing oil supply has been a suspected cause of many military interventions in the Middle East, including the Iraq War.[104] These have had dramatic knock-on effects politically and socially, whether it be contributing to the rise of ISIS or potentially triggering new wars. Even without these costly and corrosive excursions, the price of securing oil is high. The US alone spends a minimum of $81 billion on protecting its oil supply chain.[105] Decarbonisation will bring about its own set of geopolitical challenges, including the potential of new races for—and conflict over—precious Earth metals and minerals that will fuel the transition to renewable energy, but these will likely be far less toxic and dangerous than that of fossil fuels.

All of this is in sharp contrast to how we typically think of climate change as having a long history of being framed as a 'prisoner's dilemma'. Countries refuse to act first due to the high costs entailed. This assumption underlies many concerns over fair shares of emissions reductions and the proliferation of equity frameworks.[106] The framing is also wrong and does not serve the interests of the poorest and most vulnerable.[107] Instead, the co-benefits of decarbonisation appear to be largest in less developed countries.[108] Addressing environmental catastrophe is a good news story. Unlike most other global catastrophic risks, the actions needed to avoid ruin are ones we should be doing anyway. Despite this, the economic analysis and policy-making of climate change remains systematically biased towards costs, and regularly overlooks the benefits of emissions reductions.[109]

Research over the past two decades has painted both a brighter and darker future. The brighter part is the emerging evidence for co-benefits. Sparing ourselves from any potential eco-apocalypse means building a better world. That could be through deepening democracies, levelling inequalities, or improving health through decarbonisation. The darker part is the new findings suggesting that we may have underestimated just how swift and severe global ecological collapse could be.

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