

Crossing environmental thresholds determines the risk of a sixth mass extinction

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Article

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Abstract

Biodiversity loss is accelerating in the Anthropocene, yet its future trajectory remains uncertain. A key question is whether extinction risk responds linearly to environmental stress or instead exhibits threshold behaviour, as observed in past mass extinctions. Here, I integrate global datasets for five major anthropogenic drivers—climate warming, pollution, habitat loss, overexploitation, and nuclear conflict—with threatened-species patterns and projections of CO₂ emissions and human population to 2500 CE. All drivers show nonlinear, threshold-like responses, but only pollution, overexploitation, and nuclear conflict approach critical levels under plausible scenarios. Interactions among drivers amplify extinction risk by ~ 1.4-fold through synergistic population declines. Whether these drivers cross their critical thresholds results in an order-of-magnitude difference in extinction magnitude, ranging from ~ 8–70% for terrestrial species and ~ 3–46% for marine species, spanning outcomes from no mass extinction to a sixth mass extinction. In the absence of nuclear conflict, a sixth mass extinction is unlikely. If the other four drivers exceed their thresholds, a low-level mass extinction may occur, whereas remaining below these thresholds would prevent mass extinction. Therefore, limiting all five drivers to low levels is essential to avoid a mass extinction.

Introduction

Current extinction rates are estimated at ~ 1.5% for terrestrial species and ~ 0.1% for marine species over human history^{1–3}. Nevertheless, biodiversity loss is accelerating: by 2025, ~ 28% of assessed species are projected to be threatened⁴, alongside an approximately 70% decline in wild vertebrate populations over the past 50 years⁵. Despite these trends, the future trajectory and ultimate magnitude of biodiversity loss remain highly uncertain.

Earth's history records five major mass extinctions over the past ~ 500–600 million years, each associated with rapid environmental perturbations, including large igneous province volcanism and asteroid impacts^{6–11}. Although a sixth mass extinction has been proposed for the Anthropocene^{1,2,12,13}, current biodiversity loss remains comparatively limited and is often described as an “incipient” mass extinction⁹. Projections suggest that extinction rates may peak in the late 21st century and subsequently stabilize, remaining below mass-extinction thresholds^{14,15} although such estimates depend strongly on assumptions about future environmental change.

A central uncertainty is whether biodiversity loss responds linearly to environmental stress or instead exhibits threshold behaviour. Evidence from past extinction events indicates that biodiversity collapse is governed by nonlinear dynamics, with abrupt extinction pulses triggered once critical environmental thresholds are exceeded¹⁶. These pulses, occurring over timescales of years to centuries, are comparable to the duration of modern anthropogenic perturbations, indicating that threshold-based frameworks are essential for projecting future extinction risk.

Anthropogenic drivers—including climate warming, pollution, habitat loss and overexploitation—are widely recognized as primary causes of ongoing biodiversity decline^{14,15,17}. However, whether these drivers exhibit threshold responses comparable to those inferred from past mass extinctions remains unclear. Pollution can be quantitatively constrained using geochemical proxies (for example, mercury), providing a direct link between modern and ancient environmental disturbances^{14,15,18}. In contrast, overexploitation has not been systematically incorporated into quantitative estimates of future extinction magnitude. Interactions among drivers may further amplify extinction risk through compounding population declines, suggesting that combined effects may exceed the sum of individual contributions.

In addition to these ongoing drivers, low-probability but high-impact perturbations such as large-scale nuclear conflict represent a critical but underexplored risk. Nuclear conflict can induce rapid global cooling (“nuclear winter”) through stratospheric soot injection, causing abrupt declines in primary productivity and ecosystem stability. Such perturbations are comparable in magnitude and rate to environmental shocks associated with past mass extinctions and may therefore act as threshold-crossing events when superimposed on existing anthropogenic stress.

Here, we test whether major anthropogenic drivers exhibit threshold behaviour and evaluate the implications for future extinction risk. We integrate global datasets for temperature anomaly, pollution, habitat loss and overexploitation with threatened-species patterns, and assess their trajectories under projected changes in CO₂ emissions and human population, including new estimates extending from 2100 to 2500. We further evaluate how interactions among drivers amplify extinction risk and how extreme perturbations, such as nuclear conflict, may elevate extinction magnitudes beyond those driven by anthropogenic stress alone. By explicitly incorporating environmental thresholds and population-size effects, we identify critical tipping points and reassess the likelihood that future biodiversity loss could approach mass-extinction levels. Importantly, this study identifies threshold behaviour across all major drivers, quantifies their synergistic effects, and provides extinction projections constrained by both driver-based modelling and independent threatened-species dynamics, thereby distinguishing this work from previous studies.

Results

Methodological advances of this study

This study introduces several methodological advances. First, geological and anthropogenic datasets are integrated to identify threshold responses of major extinction drivers (Fig. 1; Extended Data Table 1). Second, human population dynamics are reconstructed and projected to assess long-term environmental pressure (Fig. 2d; Extended Data Table 2). Third, extinction contributions from overexploitation are quantified as an independent driver (Figs. 1d, 2f, 3d).

Fourth, revised contribution rates are estimated by accounting for overlap among extinction drivers (see “Contribution rates of extinction drivers”). Fifth, increases in extinction risk associated with wildlife

population declines under anthropogenic pressures are evaluated (Extended Data Table 3). Sixth, gradual changes in extinction magnitude are projected for the period 2100–2500 (Figs. 1–4). Finally, extinction estimates derived from anthropogenic drivers are cross-validated with those based on threatened-species data (Fig. 4).

Commonality of extinction time intervals

It is often argued that past mass extinctions occurred over timescales orders of magnitude longer than those observed today. However, this apparent discrepancy largely arises from aggregating multiple discrete extinction pulses into a single prolonged event (Extended Data Table 1). For example, the end-Permian mass extinction comprised at least two distinct phases separated by ~ 60 kyr; treating this interval as continuous substantially underestimates peak extinction rates.

Recent integration of geochemical proxies and high-resolution fossil records indicates that the principal extinction phase of the end-Permian event likely occurred within ~ 1,000 years¹⁹. Similarly, the Cretaceous–Palaeogene mass extinction unfolded over timescales of only 2–3 years, initiated by intense infrared radiation following an asteroid impact and compounded by rapid reductions in solar radiation due to stratospheric aerosols, with additional losses during subsequent warming. The end-Ordovician extinction likewise consisted of two temporally separated pulses (~ 500 kyr apart), associated with cooling followed by warming (Extended Data Table 1).

Current extinction rates for terrestrial biota are estimated at ~ 150–260 extinctions per million species per year (E/MSY), compared with background rates of ~ 0.1–1 E/MSY²⁰ (Cowie et al., 2022). Recalculating extinction rates for past mass extinctions using revised event durations yields substantially higher values than previously reported. For the end-Permian event, extinction rates are estimated at ~ 380–460 E/MSY, based on ~ 45–55% species loss in marine animals and terrestrial tetrapods over ~ 1,200 years (Extended Data Table 1). For the end-Cretaceous event, rates reach ~ 200,000–300,000 E/MSY, reflecting ~ 60% species loss over 2–3 years following the Chicxulub impact.

Previous estimates of end-Permian extinction rates (0.4–7 E/MSY)¹ are therefore likely underestimated due to the use of prolonged event durations. These revised calculations indicate that current extinction rates are comparable to those observed during past mass extinction events, highlighting the relevance of threshold-based frameworks for interpreting ongoing biodiversity loss.

Environmental thresholds for mass extinction

Mass extinctions are thought to occur when critical environmental thresholds—such as temperature limits—are exceeded, as evidenced by events associated with large igneous province volcanism, asteroid impacts and nuclear conflict scenarios¹⁶. Here, I test whether comparable threshold responses characterize anthropogenic drivers and assess the likelihood that future biodiversity loss may approach

mass-extinction levels. I focus on four key drivers—global mean temperature anomaly, pollution, habitat loss and overexploitation—and use geological and historical data to constrain their threshold values (Extended Data Table 2). This study further introduces several methodological advances (see Methods).

All examined drivers exhibit threshold behaviour, with extinction rates increasing nonlinearly once critical levels are exceeded (Fig. 1). Estimated thresholds include $\sim 5^{\circ}\text{C}$ for cooling anomalies, $\sim 9^{\circ}\text{C}$ for warming, ~ 4 – 5 -fold increases in Hg/TOC relative to baseline levels, $\sim 80\%$ deforestation, and ~ 2 – 4% species loss attributable to overexploitation (Fig. 1). These results indicate that once environmental drivers exceed their threshold values, extinction magnitudes increase rapidly.

Temporal trajectories of extinction drivers

I reconstruct temporal trajectories of key drivers—temperature anomaly and pollution (Hg/TOC_{EF})—based on CO₂ emission rates (Gt yr⁻¹) from 1700 to 2500 (Figs. 2a–c). Three emission scenarios are considered, with peaks occurring between 2020 and 2050 (Fig. 2a, Supplementary Table S1)^{21–23}. These correspond to projected global warming of ~ 2 – 5°C relative to 1850 levels (Fig. 2b). Pollution levels, expressed as Hg/TOC_{EF}, are projected to approach or exceed mass-extinction thresholds during peak emission periods (Fig. 2c).

Human population is projected to peak at ~ 10 billion around 2080, followed by a gradual decline to ~ 6 billion by 2200, ~ 4 billion by 2300, ~ 2 billion by 2400 and ~ 0.7 billion by 2500 (Fig. 2d). Using population as a proxy, I estimate associated changes in habitat loss and overexploitation (Figs. 2d–f). Forest cover reaches a minimum proportion of ~ 0.55 around 2080, indicating substantial habitat loss (Fig. 1c, Supplementary Table S2). Overexploitation is estimated to contribute $\sim 0.05\%$ extinction in marine taxa and $\sim 0.5\%$ in terrestrial tetrapods using human population (Fig. 2f).

Estimated extinction magnitudes based on anthropogenic drivers

I quantified species extinction attributable to four major anthropogenic drivers—climate warming, pollution, habitat loss and overexploitation—using threshold-based relationships between environmental stress and biodiversity loss.

Projected warming of ~ 1.9 – 4.5°C since 1850 is estimated to drive ~ 0.5 – 2% species extinction between 2080 and 2500 across marine and terrestrial systems (Fig. 3a, Supplementary Table S3). Pollution contributes ~ 1 – 2% species loss in marine systems and ~ 2 – 5% in terrestrial systems, depending on whether environmental conditions remain below or exceed critical thresholds (Fig. 3b). Habitat loss, reaching $\sim 55\%$ since $\sim 6,000$ years ago, is associated with $\sim 0.4\%$ extinction in marine taxa and $\sim 2.5\%$ in terrestrial tetrapods (Fig. 3c, Supplementary Table S4). Overexploitation contributes an additional ~ 0.05 – 0.2% and ~ 0.5 – 1.6% extinction in marine and terrestrial systems, respectively (Fig. 3d,

Supplementary Table S4). These contributions are treated as approximately additive based on independent contribution rates.

Over the past five decades (1970–2022), mean wildlife population abundance has declined to ~ 30% of baseline levels²⁴. This reduction corresponds to an approximately ~ 1.4-fold increase in extinction risk (population-size effect; Fig. 1d). Population declines driven by individual stressors can further amplify extinction risk through interactions among climate change, habitat loss, pollution and overexploitation.

Summing these contributions yields projected extinction magnitudes of ~ 3–7% in marine species and ~ 8–15% in terrestrial species when accounting for the population-size effect (Fig. 4a, Supplementary Tables S5–S7). Lower estimates reflect scenarios in which drivers remain below critical thresholds, whereas higher estimates correspond to conditions approaching or exceeding key thresholds, particularly for pollution.

As CO₂ emissions and human population growth decline, the marginal impacts of these drivers are expected to diminish, reflecting a transition towards environmental recovery and the prior loss of the most vulnerable species.

Estimated extinction magnitudes based on threatened species

Of the ~ 160,000 species assessed by the IUCN Red List⁴, over 48,000 (~ 28%) are classified as threatened (CR, EN or VU). However, these assessments represent only a small fraction of global biodiversity and are subject to well-known biases, including taxonomic (vertebrate-focused), geographic (temperate-region biased), data deficiency, and preferential assessment of species of human relevance.

Accounting for these biases—particularly using approaches such as the Sampled Red List Index (SRLI)—suggests that ~ 20–25% of all species are likely threatened globally. These corrections indicate that extinction risk among invertebrates is comparable to that of vertebrates, that plant extinction risk has been substantially underestimated, and that inclusion of Data Deficient taxa increases overall threat estimates. Consequently, the Red List Index (RLI) provides a more robust proxy for global ecosystem integrity.

Thresholds of < 250 individuals or > 80% population reduction, and 250–2,500 individuals or > 50% population reduction, correspond to extremely high and very high extinction risk, broadly consistent with CR and EN categories⁴. For example, species with ~ 10,000 individuals (the upper threshold for VU) would approach quasi-extinction (< 500 individuals) following a ~ 30% population decline (~ 0.7-fold) over ten years by ~ 2090, coinciding with the onset of global population decline (Supplementary Table 8).

Under current trajectories, projected extinction magnitudes reach ~ 4.5% by 2040, 13% by 2100 and ~ 20–25% by 2300–2500. However, these rates may decelerate as human population declines and environmental recovery begins after 2090. Overall, I estimate that ~ 9% of species could be lost by 2080,

increasing only marginally to ~ 10% by 2500 (Fig. 4b). These estimates are consistent with projections of ~ 8–15% terrestrial tetrapod species loss over 2100–2500 based on anthropogenic drivers, which corresponds to 4 to 8th fold of the present 1.6% terrestrial vertebrate. The bias of IUCN Red List assessments toward terrestrial tetrapods further supports this consistency.

Effect of nuclear conflict under anthropogenic pressures

Nuclear conflict can induce global cooling (“nuclear winter”) through the injection of soot into the stratosphere, leading to widespread declines in wildlife and human populations independently of other anthropogenic drivers^{16,25}. In the absence of pre-existing environmental stress, such conflict is estimated to cause ~ 2–4% species extinction at smaller scales and ~ 20–28% at larger scales, ranging from regional (e.g., India–Pakistan) to large-scale (e.g., USA–Russia) scenarios, excluding the effects of radioactive materials (Fig. 1e)¹⁶.

Radioactive materials that reach the stratosphere would disperse globally and be deposited via precipitation (radioactive fallout)²⁸, contaminating both marine and terrestrial environments and posing long-term ecological risks. Although the magnitude of this effect remains poorly constrained, its inclusion would likely increase extinction estimates. When population-size effects are incorporated, extinction magnitudes increase to ~ 3–6% at smaller scales and ~ 28–39% at larger scales (marine to terrestrial range).

When superimposed on existing anthropogenic pressures that have already reduced wildlife populations, extinction magnitudes are further amplified to ~ 42–46% in marine systems and ~ 63–70% in terrestrial systems at larger scales (Fig. 5; Supplementary Table S7). This corresponds to increases of ~ 1.5–1.6-fold in marine systems and ~ 1.6–1.8-fold in terrestrial systems relative to nuclear conflict alone.

Such levels of biodiversity loss approach those observed during past mass extinction events and may be consistent with a sixth mass extinction scenario (Fig. 5).

Discussion

Only a limited number of studies (approximately four) have attempted to quantify the future magnitude of species extinction. Two studies projected extinction based on threatened-species data up to 2100, estimating that ~ 10% of terrestrial tetrapod species may be lost^{26,27}. Other studies, including those by the present author, combined geological and historical data with projections of anthropogenic CO₂ emissions and human population to estimate extinction magnitudes for marine animals and terrestrial tetrapods based on individual drivers^{14,15}.

However, the former studies do not extend to estimates of the ultimate extinction magnitude in the Anthropocene, whereas the latter approaches attempt such long-term projections but assume linear responses and do not incorporate threshold effects.

In contrast, the present study constrains post-2100 population dynamics, which have previously been highly uncertain, incorporates overexploitation as an additional driver, and identifies threshold behaviour across all major drivers. Based on these thresholds, I provide revised estimates of extinction magnitude and project the long-term trajectory of biodiversity loss by integrating population declines across threatened-species categories and their synergistic effects.

Although the resulting extinction estimates are intermediate between those reported previously^{14,15}, this agreement is coincidental and arises from offsetting effects of incorporating both threshold behaviour and overexploitation. Importantly, the present framework improves consistency and predictive robustness. Notably, extinction projections derived from the four drivers closely match those independently estimated from threatened-species data up to 2500, supporting the reliability of the approach.

Whether environmental drivers exceed their critical thresholds can lead to more than a twofold increase in extinction magnitude, and up to an order-of-magnitude increase under nuclear conflict scenarios. Preventing the crossing of these thresholds should therefore be a primary objective. A key contribution of this study is the demonstration that each major driver possesses a threshold capable of triggering mass extinction, together with quantitative constraints on these threshold levels. Notably, pollution, overexploitation, and nuclear conflict are identified as the drivers most likely to approach or exceed these thresholds under plausible future scenarios.

I further demonstrate that population declines driven by individual stressors increase extinction risk (the “population-size effect”). Even when thresholds are not exceeded, reductions in population size by an order of magnitude substantially elevate extinction vulnerability. The combined effects of the four ongoing anthropogenic drivers and potential nuclear conflict further amplify extinction magnitudes beyond those caused by individual drivers. By quantifying these interaction effects for the first time, this study improves the accuracy of extinction projections.

A key control on future biodiversity loss is the threshold behaviour of pollution. Assuming that pollution scales with CO₂ emissions, the mass-extinction threshold corresponds to ~ 2.5°C warming above pre-industrial levels by 2100. Avoiding this threshold is therefore critical. In practical terms, this requires limiting pollution of the atmosphere, soils and oceans by toxic gases, chemicals and plastics. In parallel, sustainable use of wildlife is essential to prevent overexploitation from exceeding its threshold.

If none of the four anthropogenic drivers or nuclear conflict exceeds their respective thresholds, extinction may be limited to ~ 3% in marine and ~ 8–9% in terrestrial animal species. However, if pollution and overexploitation cross their thresholds, extinction magnitudes may increase to ~ 5–7% and ~ 11–15%, consistent with estimates based on threatened species. If nuclear conflict exceeds its threshold, extinction could increase tenfold in marine and five-sevenfold in terrestrial, potentially leading to a moderate-to major scale mass extinction corresponding to the sixth mass extinction (Fig. 5).

Anthropogenic emissions are projected to peak between 2020 and 2060, and global population is expected to decline after 2100, reducing overall environmental pressure (Fig. 2d). Consequently, extinction rates are unlikely to exceed peak levels beyond the 21st century. Although biodiversity loss may intensify during this period, it is unlikely to develop into a sustained mass extinction in the absence of nuclear conflict, provided that critical thresholds are not crossed.

Modern human society relies heavily on subsurface resources, which drive both climate warming and pollution. Population growth has expanded agriculture and urbanization, resulting in habitat loss and overexploitation. At the same time, the proliferation of nuclear weapons increases the risk of cascading conflict once initiated. Large-scale nuclear war would likely impose the most severe impacts on both biodiversity and human populations. Reducing these risks requires decreasing dependence on fossil and other subsurface resources, limiting and ultimately eliminating nuclear arsenals, and expanding technologies to reduce pollution.

Even when thresholds are not exceeded, the population-size effect implies that extinction risk can still increase as species abundances decline. Therefore, all drivers must be mitigated. Conservation and restoration of natural ecosystems—particularly tropical forests—together with limiting global warming, are essential for maintaining biodiversity and stabilizing the Earth system.

Effective risk mitigation requires recognition by nations of the need to avoid exceeding environmental thresholds through sustainable resource use, pollution control and nuclear disarmament. Establishing shared international targets is essential, but must be accompanied by coordinated global implementation.

Because both global population and CO₂ emissions are projected to peak during the 21st century, this period represents a critical window for humanity. Successfully navigating it with minimal biodiversity loss will require reduced resource consumption, accelerated decarbonization and sustained international cooperation.

Overall, projected species loss ranges from ~ 3% to 46% in marine systems and ~ 8% to 70% in terrestrial systems, depending on human responses. These results highlight that avoiding critical environmental thresholds—particularly for pollution, overexploitation and nuclear conflict—is key to constraining future extinction risk.

Methods

Calculation of human population

Human population from 2000 to 2500 CE was estimated using global population projections from Ritchie et al.²⁹ for the period 2000–2100 and birth and death data for the period 2100–2500. Beyond 2100, it is assumed that the birth rate and death rate of each birth cohort decline at a constant rate, based on the average decline observed from 2080 to 2100. A constant decline rate in birth population

and related mortality is assumed after 100 years from the birth year after 2100. An example equation for estimating population in 2120 is:

$$P_{(2120)} = P_{(2100)} + B_{(2120-2100)} - D_{(2120-2100)},$$

where P is population, B is birth population, and D is death population. Subscript numbers refer to calendar years.

Extinction models based on Phanerozoic data

The warming-based extinction model is derived from sea surface temperature (SST) anomalies associated with key events, including major mass extinctions, the Paleocene–Eocene Thermal Maximum (PETM), the Popigai impact, and recent conditions (1700 and 2000 CE) (Fig. 1a; Extended Data Table 4). The PETM (~ 55 Ma), characterized by ~ 6.5°C global warming in the absence of substantial deforestation or elevated pollution, provides an analogue for isolating extinction responses to temperature increase alone^{14,15}. These relationships are used to constrain the independent contribution of warming to extinction in both marine and terrestrial systems.

Pollution-driven extinction is constrained using enrichment factor (EF) values of mercury-to-total organic carbon ratios (Hg/TOC [ppb wt%⁻¹]_{EF}), which serve as geochemical proxies for environmental toxicity during past events and the period 1700–2000 CE (Fig. 1b; Extended Data Table 2)^{15,30}. The EF is defined as the ratio of mean peak values during an event interval to corresponding background levels. Major Hg sources include volcanism, biomass burning, soil and vegetation emissions, oceanic evasion and industrial activity³¹, with primary contributions from volcanic and industrial sources and episodic inputs from impact events³². The co-release of Hg and carbon from subsurface reservoirs during volcanism, impacts and fossil fuel combustion links pollution and warming processes across both the Phanerozoic and the present, supporting the use of Hg/TOC as a unified proxy for pollution intensity. Experimental studies indicate that both Hg and TOC decrease at ~ 400–500°C in geological samples.

The deforestation model is based on four lines of evidence: (i) the absence of tree fossils following the end-Permian mass extinction³³; (ii) palaeoclimate reconstructions during the Cretaceous–Palaeogene (K–Pg; Chicxulub impact³⁴) and mid-Norian (Manicouagan impact³⁵) extinction events; (iii) long-term and recent deforestation trends, including ~ 40% global forest loss from 4000 BCE to 2000 CE and ~ 5.4% loss between 1990 and 2005³⁶; and (iv) the positive correlation between deforestation and human population, used to project future trends (2060–2500)³⁷. Palaeoclimate reconstructions are used to estimate global vegetation loss based on forest distributions across tropical, temperate and continental climate zones (Fig. 1c; Supplementary Fig. S1).

In this framework, terrestrial habitat loss is treated as equivalent to deforestation. Deforestation is further linked to marine habitat degradation through nutrient-driven eutrophication, whereas oceanic anoxia is incorporated as part of the warming-driven extinction pathway.

Models based on Holocene–Anthropocene data

Baseline extinction rates are set at $\sim 1.5\%$ for terrestrial species and $\sim 0.1\%$ for marine species in 2010, based on previous syntheses^{1–3,38}. Modern and projected global temperature anomalies from 1700 to 2100 are derived from Intergovernmental Panel on Climate Change (IPCC) assessments^{22,23}, with projections for 2100–2500 based on the IPCC Fifth Assessment Report²¹.

Pollution levels between 1700 and 2010 are estimated using peak-to-background mercury (Hg) ratios from environmental records^{39,40}. Future Hg levels (2010–2500) are inferred from projected CO₂ emissions, assuming proportional co-emission of Hg and CO₂ during fossil fuel combustion⁴¹.

Deforestation trends from 1700 to 2050 are reconstructed from historical records, including $\sim 40\%$ global forest loss from 4000 BCE to 2000 CE and $\sim 5.4\%$ loss between 1990 and 2005³⁶. Projections for 2060–2500 are derived from observed relationships between human population and habitat loss, including forest cover^{36,37,42}.

Because overexploitation lacks a direct geological analogue, it is estimated using threatened-species frameworks^{2,17}. Three categories—CR, EN and VU—are applied, with corrected extinction fractions of 4.5%, 13% and 23%, respectively (Extended Data Table 4). Corresponding population decline rates over three generations (CR = 0.8, EN = 0.5, VU = 0.2) and characteristic population thresholds (CR < 250, EN < 2,500, VU < 10,000 individuals) are used to parameterize extinction risk, as these metrics form the basis of category definitions (Fig. 1d)⁴.

Species included in endangered-species assessments are typically selected as indicator taxa, which may lead to overestimation of global extinction percentages. Accordingly, corrected extinction fractions are applied as described above.

Extinction timing and magnitude are further constrained using population-change rates and population sizes ranging from 1,000 to 128,000 individuals, establishing relationships between time and extinction probability (Fig. 1d). These relationships are also used to infer thresholds for overexploitation-driven extinction.

The relationship between vertebrate population trends relative to 1970 and extinction percentages is derived from WWF²⁴ and Fig. 1c, assuming proportionality between habitat area and animal population size (Fig. 4b).

Contribution rates of extinction drivers

To account for interdependence among the four drivers, contribution rates were assigned based on existing estimates of their relative contributions to contemporary extinction.

Climate change

The Paleocene–Eocene Thermal Maximum (PETM; ~55 Ma), characterized by ~ 6.5°C global warming without substantial pollution or deforestation, provides an analogue for climate-driven extinction^{14,15}. This estimate is derived from sea surface temperature anomalies of 4–5°C⁴³ and converted to global mean values following Kaiho⁸. The extinction percentage is set at ~ 5%, corresponding to the upper range of background extinction in Phanerozoic records¹⁵. The contribution rate is set at 1.0, reflecting the global and systemic influence of climate change.

Pollution

Pollution typically affects geographically limited regions, allowing refugia for species persistence. Based on current estimates indicating lower contributions than habitat loss and overexploitation (> 0.2; COP15)⁴⁴, and the greater buffering capacity of marine systems, contribution rates are set at 0.1 for terrestrial environments and 0.05 for marine environments.

Habitat loss

In terrestrial systems, where ~ 80–90% of species depend on forests⁴⁵, the contribution rate is set at 0.6, consistent with estimates exceeding 0.5⁴⁴. In marine systems, habitat loss is expressed indirectly through cascading processes (deforestation → soil erosion → nutrient loading → harmful algal blooms), and is therefore assigned a lower contribution rate of 0.1. Habitat-loss effects are modelled as a function of population size.

Overexploitation: As overexploitation lacks a direct geological analogue, its contribution is modelled dynamically as a function of human population and species population size. Extinction percentages increase with human population growth. Additional constraints are derived from cumulative extinction fractions of threatened categories (CR: 4.5%, CR + EN: 13%, CR + EN+VU: 23%) and corresponding population decline rates over three generations (CR = 0.8, EN = 0.5, VU = 0.2).

These estimates are assumed to apply until ~ 2080, when human population is projected to peak, after which extinction rates are expected to decline in parallel with decreasing population. To account for shared effects among drivers, aggregate contribution rates are set at 0.2 for terrestrial systems and 0.33 for marine systems, following COP15 estimates⁴⁴.

Together, these calibrated parameters enable estimation of total extinction magnitude by integrating multiple anthropogenic stressors. Although each driver exhibits distinct dynamics, their combined effects are approximated using additive approaches that account for partial overlap.

Population-size effect on extinctions

Population decline rates are set at 0.2, 0.5 and 0.8 for CR, EN and VU categories, respectively, over three generations (~ 10 years for vertebrates; Extended Data Table 4, Supplementary Table S8, Fig. 1d)⁴. These values are incorporated into the extinction model to account for population-size effects.

Extinction magnitude (E) is expressed as:

$$E (\%) = OE \times 1.4,$$

where OE represents the original extinction percentage.

The scaling factor of 1.4 is derived from Fig. 1d (3.0/2.2), corresponding to a decline from 10,000 to 1,000 individuals by 2080 under a population reduction rate of ~ 0.3 (intermediate between CR and EN categories). This factor captures the population-size effect, whereby extinction risk accelerates as population size declines.

When population size falls below ~ 500 individuals, extinction risk increases sharply due to Allee effects, including reduced mate availability and diminished cooperative interactions. These processes generate nonlinear increases in extinction probability at low population sizes.

The factor of 1.4 is applied to extinction estimates from anthropogenic drivers to account for their partial interdependence: climate warming and pollution are linked to CO₂ emissions, whereas habitat loss and overexploitation are linked to human population growth. The same population-size amplification is also applied to extinction estimates associated with radioactive materials dispersed globally during nuclear conflict.

Because nuclear conflict operates independently of these anthropogenic drivers, the amplification factor is applied separately to extinction estimates for nuclear-conflict scenarios.

Data availability

Data is provided within the manuscript and supplementary information files.

Declarations

Declaration of competing interest

The author declares no competing interests relevant to this study.

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Declaration

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Author Contribution

Kunio Kaiho: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review and editing.

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Data Availability

Data availability Data is provided within the manuscript file. Related data are available from open access articles, Kaiho (2022a) and Kaiho (2025).

References

1. Barnosky, A. D. et al. Has the Earth's sixth mass extinction already arrived? *Nature* **471**, 51–57 (2011).
2. Ceballos, G. et al. Accelerated modern human-induced species losses: Entering the sixth mass extinction. *Sci. Adv.* **1**, e1400253 (2015).
3. McCauley, D. J. et al. Marine defaunation: Animal loss in the global ocean. *Science* **347**, 1255641 (2015).
4. IUCN. The IUCN Red List of Threatened Species, Version 2025-2 (2025). (2025).
5. Grooten, R. E. A., Juffe Bignoli, M., Petersen, T., Eds & D. & (Living Planet Report 2022 – Building a nature-positive society. *Almond* (WWF, 2022).
6. Sepkoski, J. J. Jr. Patterns of Phanerozoic extinctions: A perspective from global data bases, in: Global Event Stratigraphy, edited by Walliser, O. H., Springer-Verlag, Berlin, Heidelberg, Germany, 35–52 (1996).
7. Bambach, R. K. Phanerozoic biodiversity mass extinctions. *Ann. Rev. Ear Planet. Sci.* **34**, 127–155 (2006).
8. Kaiho, K. Relationship between extinction magnitude and climate change during major marine and terrestrial animal crises. *Biogeosciences* **19**, 3369–3380 (2022).
9. Marshall, C. R. Forty years later: The status of the Big Five mass extinctions. *Camb. Prisms Extinction*. **1** (e5), 1–13 (2023).
10. Rampino, M. R., Caldeira, K. & Rodriguez, S. Sixteen mass extinctions of the past 541 My correlated with 15 pulses of Large Igneous Province (LIP) volcanism and the 4 largest extraterrestrial impacts. *Glob Planet. Chang.* **234**, 104369 (2024).
11. Kaiho, K. Mechanisms of global climate change during the five major mass extinctions. *Sci. Rep.* **15**, 16498 (2025).

12. Wake, D. B. & Vredenburg, V. T. Are we in the midst of the sixth mass extinction? A view from the world of amphibians. *Proc. Natl Acad. Sci. USA* **105**, 11466–11473 (2008).
13. Waters, C. N. et al. The Anthropocene is functionally and stratigraphically distinct from the Holocene. *Science* **351**, aad2622 (2016).
14. Kaiho, K. Extinction magnitude of animals in the near future. *Sci. Rep.* **12**, 19593 (2022).
15. Kaiho, K. An animal crisis caused by pollution, deforestation, and warming in the late 21st century and exacerbation by nuclear war. *Heliyon* **9**, e15221 (2023).
16. Kaiho, K. Threshold dynamics of mass extinctions and human famine risk. *Evol. Earth.* **4**, 100114 (2026).
17. Harnic, P. G. et al. Extinctions in ancient and modern seas. *Trends Ecol. Evol.* **27**, 608–617 (2012).
18. Grasby, S. E., Them, I. I., Chen, T. R., Yin, Z., Ardakani, O. H. & R. & Mercury as a proxy for volcanic emissions in the geologic record. *Earth Sci. Rev.* **196**, 102880 (2019).
19. Saito, R. et al. Centennial scale sequences of environmental deterioration preceded the end-Permian mass extinction. *Nat. Commun.* **14**, 2113 (2023).
20. Cowie, R. H., Bouchet, P. & Fontaine, B. The sixth mass extinction: Fact, fiction or speculation? *Biol. Rev.* **97**, 640–663 (2022).
21. IPCC 2014. : Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. (2014). Climate Change (2014).
22. O'Neill, B. C. et al. The scenario model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model. Develop.* **9**, 3461–3482 (2016).
23. IPCC. Summary for policymakers, in: V. Masson-Delmotte, et al. (Eds.), Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. (Cambridge University Press, 3–32, 2021). (2021).
24. Grooten, R. E. A., Juffe Bignoli, M. & Petersen, T. (eds) *Living Planet Report 2022 – Building a nature-positive society*. Almond (WWF, 2022).
25. Xia, L. et al. Global food insecurity and famine from reduced crop, marine fishery and livestock production due to climate disruption from nuclear war soot injection. *Nat. Food.* **3**, 586–596 (2022).
26. Andermann, T., Faurby, S., Turvey, S. T., Antonelli, A. & Silvestro, D. The past and future human impact on mammalian diversity. *Sci. Adv.* **6**, eabb2313 (2020).
27. Toussaint, A. et al. Extinction of threatened vertebrates will lead to idiosyncratic changes in functional diversity across the world. *Nat. Commun.* **12**, 5162 (2021).
28. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), New York, NY (United States). Sources and effects of ionizing radiation. UNSCEAR 2000 report to the General Assembly, with scientific annexes. Volume I: Sources. UN. (2000).
29. Ritchie, H. et al. Population Growth. Published online at OurWorldinData.org. (2023). Retrieved from: <https://ourworldindata.org/population-growth> [Online Resource].

30. Grasby, S. E., Liu, X., Yin, R., Ernst, R. & Chen, Z. Toxic mercury pulses into late Permian terrestrial and marine environments. *Geology* **48**, 830–833 (2020).
31. Zhang, Y. et al. An updated global mercury budget from a coupled atmosphere-land-ocean model: 40% more re-emissions buffer the effect of primary emission reductions. *One Earth*. **6**, 316–325 (2023).
32. Fendley, I. M. et al. Constraints on the volume and rate of Deccan Traps flood basalt eruptions using a combination of high-resolution terrestrial mercury records and geochemical box models. *Earth Planet. Sci. Lett.* **524**, 115721 (2019).
33. Sun, Y. et al. Lethally hot temperatures during the Early Triassic greenhouse. *Science* **338**, 366–370 (2012).
34. Kaiho, K. & Oshima, N. Site of asteroid impact changed the history of life on Earth: the low probability of mass extinction. *Sci. Rep.* **7**, 14855 (2017).
35. Kaiho, K. & Oshima, N. The significance of impact-induced hydrocarbon soot aerosols in global climate change and extinctions. *Palaeogeogr Palaeoclimatol Palaeoecol.* **678**, 113237 (2025).
36. Sandker, M., Finegold, Y., D’Annunzio, R. & Lindquist, E. Global deforestation patterns: comparing recent and past forest loss processes through a spatially explicit analysis. *Int. Rev.* **19**, 350–368 (2017).
37. Jha, S. & Bawa, K. S. Population growth, human development, and deforestation in biodiversity hotspots. *Conserv. Biol.* **20**, 906–912 (2005).
38. Monte-Luna et al. A review of recent and future marine extinctions. *Cambridge Prisms: Extinction* **1**, e13, 1–9 (2023).
39. Yin, R. et al. Historical records of mercury stable isotopes in sediments of Tibetan Lakes. *Sci. Rep.* **6**, 23332 (2016).
40. Kurz, A. Y., Blum, J. D., Washburn, S. J., Baskaran, M. & Changes in the mercury isotopic composition of sediments from a remote alpine lake in Wyoming. *Sci. Total Environ.* **669**, 973–982 (2019).
41. Kim, M. K. & Zoh, K. D. Fate and transport of mercury in environmental media and human exposure. *J. Prev. Med. Public. Health.* **45**, 335–343 (2012).
42. DeFries, R. S., Rudel, T., Uriarte, M. & Hansen, M. Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nat. Geosci.* **3**, 178–181 (2010).
43. Zachos, J. C. et al. A transient rise in tropical sea surface temperature during the Paleocene-Eocene thermal maximum. *Science* **302**, 1551–1554 (2003).
44. Kunming-Montreal Global Biodiversity Framework (GBF). *CBD (Convention on Biological Diversity)*, (2022). (2022).
45. Dirzo, R. et al. Defaunation in the Anthropocene. *Science* **345**, 401–406 (2014).
46. Zimmit, J. B., Holland, S. M., Finnegan, S. & Marshall, C. R. Recognizing pulses of extinction from clusters of last occurrences. *Paleontology* **64**, 1–20 (2021).

47. Song, H., Wignall, P. B., Tong, J. N. & Yin, H. F. Two pulses of extinction during the Permian-Triassic crisis. *Nat. Geosci.* **6**, 52–56 (2013).

48. Wing, S. L. et al. Transient floral change and rapid global warming at the Paleocene-Eocene boundary. *Science* **310**, 993–996 (2005).

49. Jaramillo, C. et al. Effects of rapid global warming at the Paleocene-Eocene boundary on neotropical vegetation. *Science* **330**, 957–961 (2010).

50. CRediT authorship contribution statement.

51. Kunio Kaiho. Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review and editing.

Figures

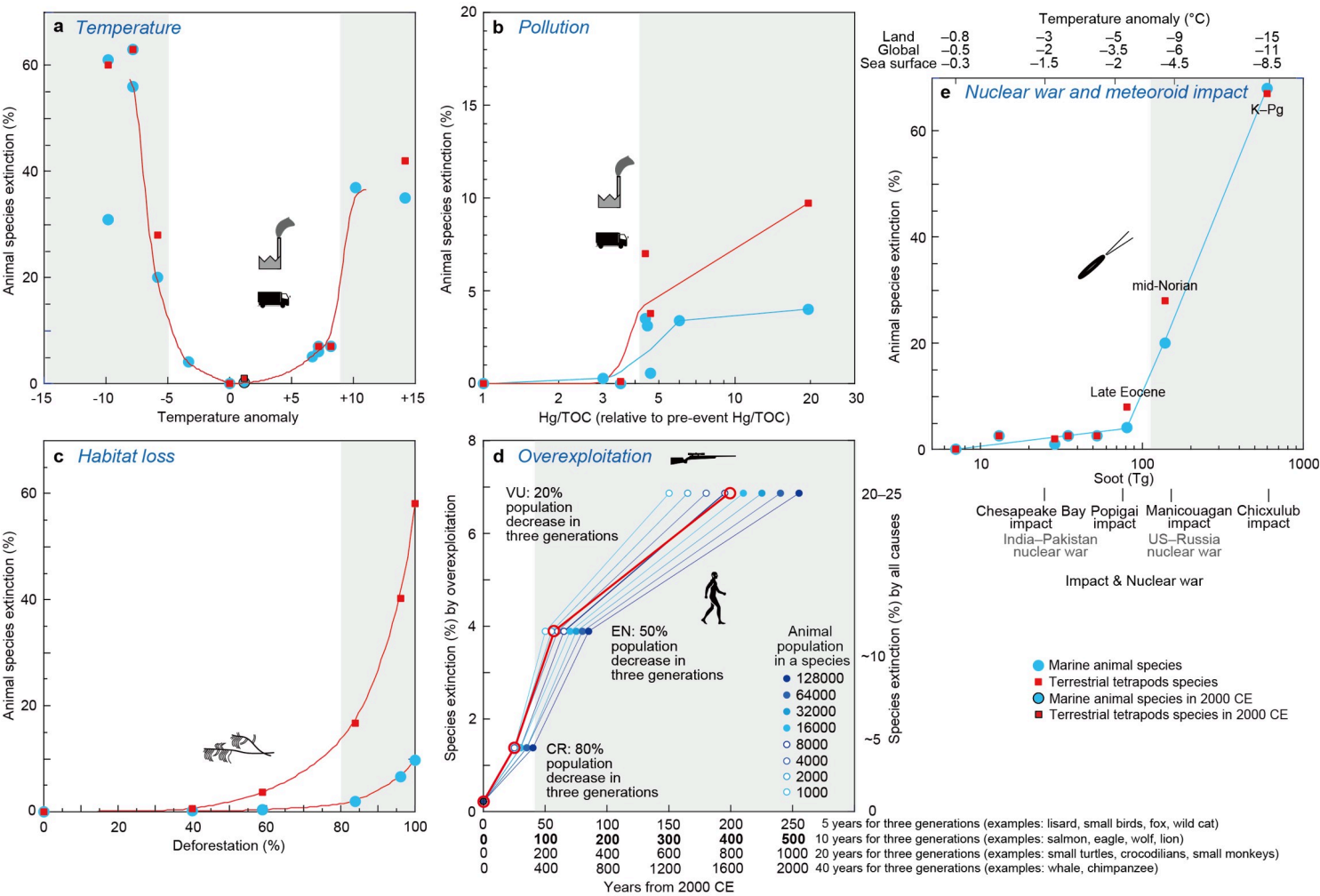


Figure 1

Relationships between extinction drivers and cumulative animal species loss. Relationships between environmental drivers—global mean surface temperature anomaly (cooling and warming), pollution, habitat loss, overexploitation and stratospheric soot—and cumulative animal species extinction

percentages derived from geological and historical data. In **a**, cooling and warming data are from Zimmit et al.⁴⁶, Song et al.⁴⁷ and Kaiho^{8,11}; red squares denote terrestrial tetrapods and blue circles denote marine species. In **b**, pollution data are from Kaiho¹⁵. In **c**, habitat loss (deforestation) data are compiled from Wing et al.⁴⁸, Jaramillo et al.⁴⁹, Sun et al.³³, Sandker et al.³⁶ and vegetation-area estimates based on climate classification maps (Supplementary Fig. S1). In **d**, projected extinction magnitudes are estimated from threatened-species proportions (CR, EN and VU) assuming generation times of 5–40 years⁴. In **e**, nuclear-conflict-related extinction data are from Kaiho¹⁶. K–Pg: Cretaceous-Palaeogene boundary. Grey shading indicates values exceeding thresholds associated with minor mass extinctions (Extended Data Table 1). All data have uncertainties of approximately $\pm 10\%$. Silhouettes were created by the author or derived from publicly available sources.

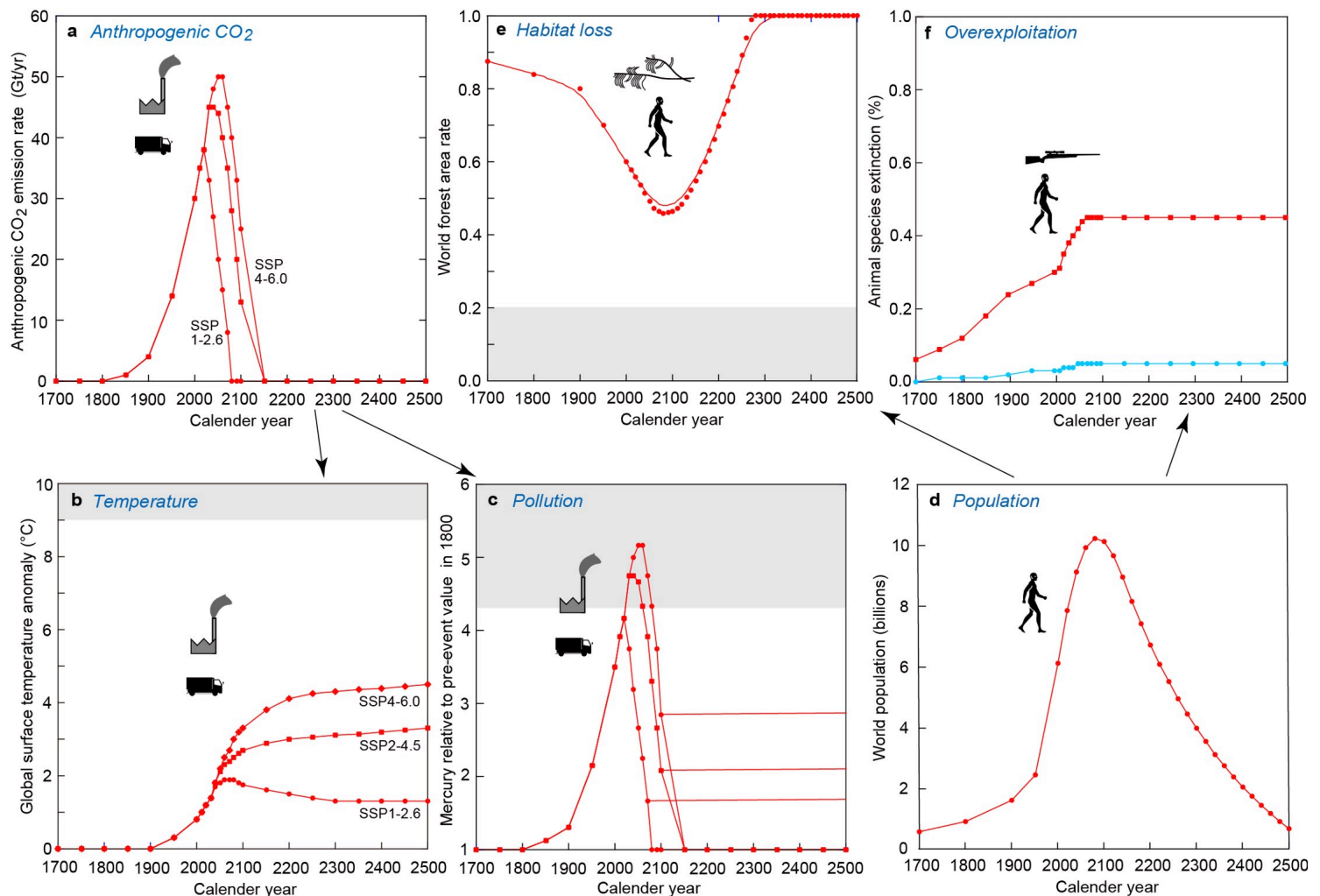


Figure 2

Trajectories of anthropogenic drivers and human population (1700–2500 CE). Temporal changes in anthropogenic extinction drivers, CO₂ emission rates and global human population. Future projections in **b** and **c** are derived from CO₂ emission scenarios in **a** (Supplementary Table S1). Curves represent SSP1-2.6, SSP2-4.5 and SSP4-6.0 scenarios. Future projections in **e** and **f** are based on population trends in **d** (Extended Data Table 3; Supplementary Tables S2 and S3). Grey shading indicates values exceeding

environmental thresholds for mass extinction. Horizontal lines in **c** and **e** denote low-recovery scenarios. In **f**, blue and red symbols represent marine species and terrestrial tetrapods, respectively.

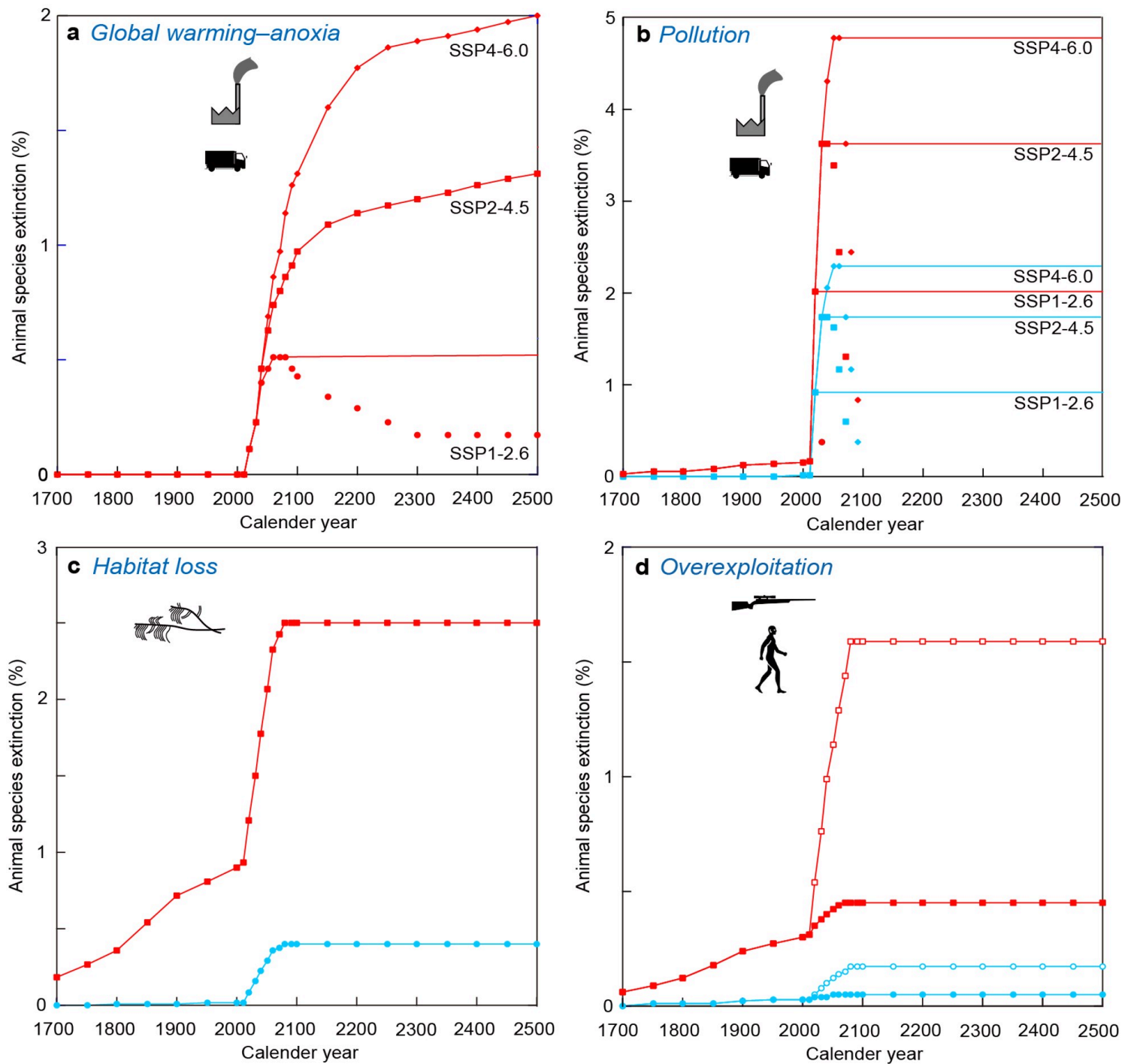


Figure 3

Cumulative extinction attributable to anthropogenic drivers (1700–2500 CE). Projected cumulative extinction percentages for animal species driven by climate warming, pollution, habitat loss and overexploitation. In **c** and **d**, blue and red symbols represent marine species and terrestrial tetrapods, respectively. Open red symbols in **d** indicate estimates based on IUCN threatened-species data⁴

assuming constant contribution rates to 2500. See Extended Data Table 4, Fig. 4b and Supplementary Tables S3 and S4 for details.

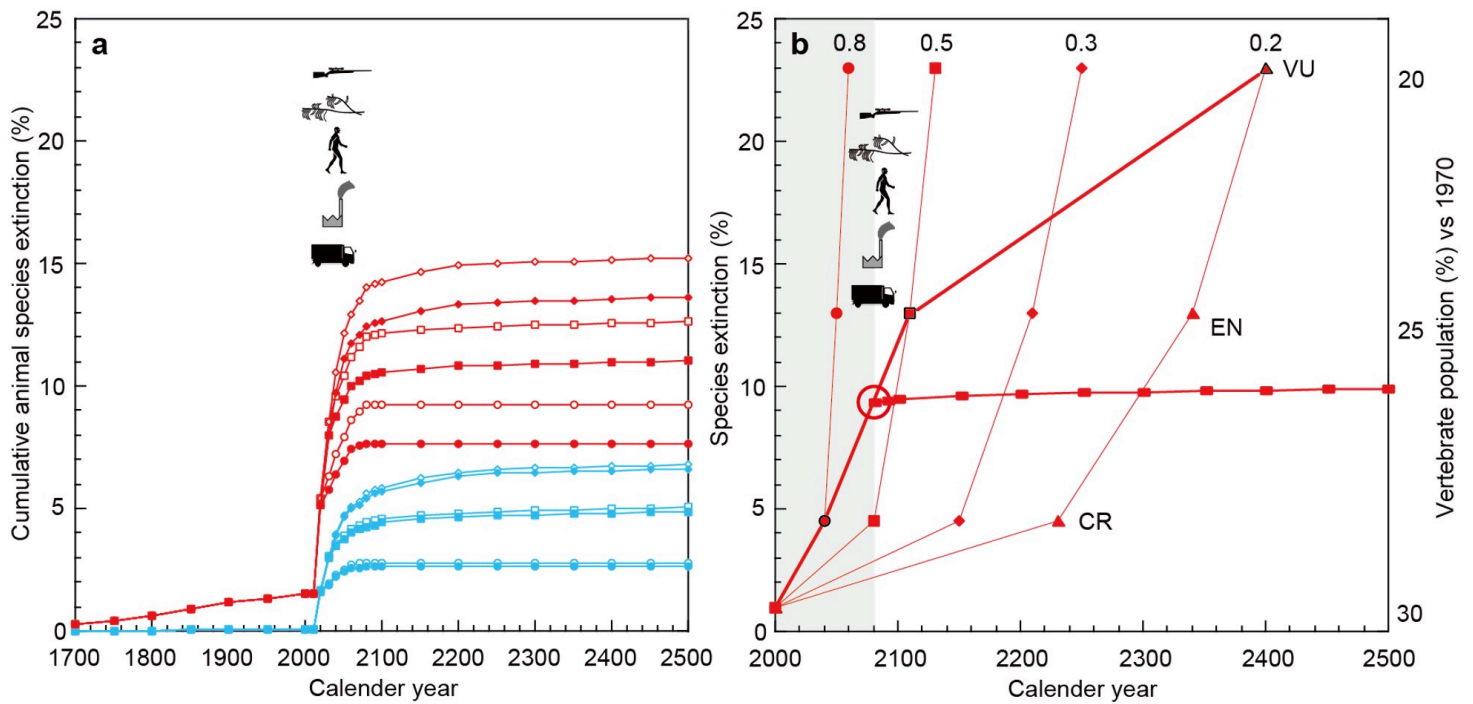


Figure 4

Projected cumulative extinction magnitude from 1700 to 2500 CE.

In **a**, cumulative extinction percentages from the four anthropogenic drivers (Fig. 3) are summed and scaled by a factor of 1.2 to account for increased extinction risk associated with declines in mean wildlife population abundance to ~30% of baseline over the past five decades²⁴. Open symbols indicate estimates based on threatened-species data⁴, assuming a constant contribution of overexploitation since 2000 CE. Blue and red symbols represent marine species and terrestrial tetrapods, respectively (Supplementary Tables S5 and S6). In **b**, thin red lines show extinction estimates derived from the proportions of threatened species (CR, EN and VU; corrected to 4.5%, 13% and 23%) and their associated population decline rates (CR = 0.8, EN = 0.5, VU = 0.2 over three generations⁴). Black-outlined symbols connected by thick red lines incorporate both population decline rates and species-specific population thresholds (CR < 250, EN < 2,500, VU < 10,000). The large open circle indicates ~9% species loss at ~2080 CE, immediately prior to projected environmental recovery. Post-2080 trajectories follow the same rates as shown in **a**. Vertebrate population trends relative to 1970 are from WWF²⁴.

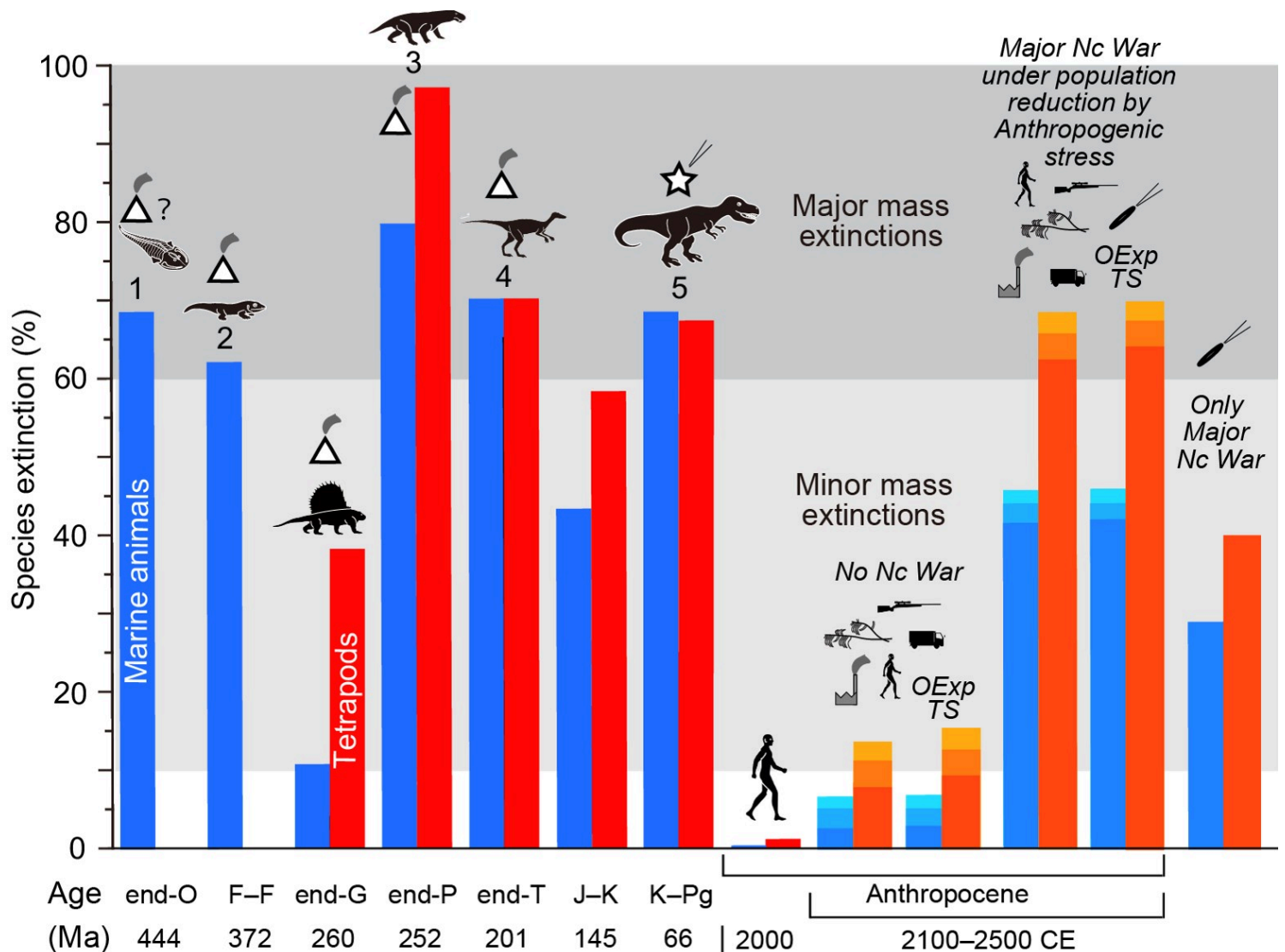


Figure 5

Extinction magnitudes during Phanerozoic mass extinctions and projected Anthropocene scenarios.

Cumulative extinction magnitudes for marine animals (blue to light blue) and terrestrial tetrapods (red to orange) are compared across major Phanerozoic mass extinctions and projected Anthropocene scenarios. Numbers 1–5 denote the “Big Five” mass extinctions. Dark-coloured bars represent geological records, whereas lighter colours indicate projections under different climate scenarios (SSP1-2.6, SSP2-4.5 and SSP4-6.0, from dark to light shades). Abbreviations: O, Ordovician; F–F, Frasnian–Famennian; G, Guadalupian; P, Permian; T, Triassic; J–K, Jurassic–Cretaceous; K–Pg, Cretaceous–Palaeogene. Italic labels denote scenario types, including nuclear conflict (Nc war) and overexploitation based on threatened species (OExp TS). Silhouettes represent characteristic vertebrate taxa for each interval and Anthropocene drivers. Geological data are from Kaiho⁸; Anthropocene projections are from Supplementary Table S8.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [KaihoFERSI12.docx](#)
- [ExtendedData.docx](#)