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Research article

An animal crisis caused by pollution, deforestation, and warming in the late 21st century and exacerbation by nuclear war

Kunio Kaiho

Department of Earth Science, Tohoku University, Sendai 980-8578, Japan

A R T I C L E I N F O

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A B S T R A C T

An environmental–animal crisis is currently ongoing and is becoming increasingly severe due to human activity. However, the magnitude, timing, and processes related to this crisis are unclear. This paper clarifies the likely magnitude and timing of animal extinctions and changes in the contribution rates of select causes (global warming, pollution, deforestation, and two hypothetical nuclear conflicts) of animal extinctions during 2000–2300 CE. This paper demonstrates that an animal crisis marked by a 5–13% terrestrial tetrapod species loss and 2–6% marine animal species loss will occur in the next generation during 2060–2080 CE if humans do not engage in nuclear wars. These variations are due to magnitudes of pollution, deforestation, and global warming. The main causes of this crisis will change from pollution and deforestation to deforestation in 2030 under the low CO_2 emission scenarios but will change from pollution and deforestation to deforestation in 2070 and then to deforestation and global warming after 2090 under the medium CO_2 emissions. A nuclear conflict will increase animal species loss up to approximately 40–70% for terrestrial tetrapod species and 25–50% for marine animal species, including errors. Therefore, this study shows that the animal species conservation priority is to prevent nuclear war, reduce deforestation rates, decrease pollution, and limit global warming, in this order.

1. Introduction

Humans face multiple crises, such as anthropogenic environmental perturbations, potential nuclear war, and potential extinction of numerous animal species [1–4]. The current extinction rate for animal species is increasing in parallel with anthropogenic-induced rapid environmental perturbations, which are driven by global warming, pollution, and deforestation [3,4]. The sixth mass extinction in hundreds of years has been proposed as a potential future event [1]. The magnitude of past mass extinctions can be monitored by global surface temperature anomalies [5–7]. Two papers have suggested the possibility of the sixth mass extinction; however, a third paper demonstrated that the sixth mass extinction (>60% species loss) is an overestimation [7]. Analyses based on threatened species data indicate an approximately 10% loss in mammals, birds, and reptiles and an approximately 30% loss in amphibian and freshwater fish depending on extinction scenarios [8,9]. However, these predictions of future extinctions do not show the timing of the maximum animal loss. If a nuclear war occurred in an area, then the fire from the urban areas would lead to smoke in the stratosphere, which would cause global cooling due to a reduction in sunlight reaching the surface; this scenario is referred to as nuclear winter [10, 11].

Kaiho [4] predicted a 10–15% animal species loss at approximately 2100 CE under the most likely climate scenario with no nuclear

E-mail address: kunio.kaiho.a6@tohoku.ac.jp.

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war based on the similarity among the causes of the past mass extinctions and the current biotic crisis. The mass extinction causes are global warming, pollution, deforestation, and sunlight reduction with global cooling, which are induced by anthropogenic perturbation and nuclear war in the near future [4]. These activities were also due to large volcanic events and projectile impacts in the geologic ages, leading to the current prediction. The author indicated that the sixth major mass extinction (defined as > 60% species loss) will be prevented, but a minor mass extinction event, 20–50% animal species loss (1% now), will occur at approximately 2100 CE, when humans engage in nuclear war and/or fail to stop increasing greenhouse gas (GHG) emissions, pollution, and deforestation.

There are large variations in future extinction percentages relating to the magnitudes of anthropogenic CO_2 emissions as well as deforestation [4]. The likely CO_2 emission scenarios are Shared Socioeconomic Pathway (SSP) 1–1.9, SSP1-2.6, SSP2-4.5, and SSP4-6.0, which would result in 1.6, 1.9, 2.7, and 3.3 °C of global warming above the preindustrial level by 2100, respectively, because CO_2 emissions will decrease from 2022 to 2050 under the four scenarios [12,13] (Fig. 1a). Scenarios SSP1-1.9 and SSP1-2.6 are referred to as low CO_2 emission scenarios since they result in ~1.8 °C of global warming (implemented by current world politics). The medium CO_2 emission scenarios are SSP2-4.5 and SSP4-6.0, which would result in ~3 °C of global warming (the most likely scenario presented by Kaiho [4]). The high CO_2 emission scenarios are SSP3-7 and SSP5-8.5 (these assume an increase in CO_2 emissions until 2080–2100), which would result in 4–5 °C of global warming by 2100. Furthermore, 7–8.5 °C of global warming is expected by 2500 [14] under SSP5-8.5, which is the worst-case scenario as discussed in Kaiho [4] and assumes that the global CO_2 reductions currently implemented are abandoned [12–14]). Therefore, only the first four scenarios are considered in this study for predicting future extinctions.

Although a major nuclear war could itself cause a minor mass extinction [4], the potential magnitude of this extinction event is unclear because it will increase if a nuclear war occurs during a decrease in animal populations resulting from anthropogenic disturbances to the environment (this was not considered in Kaiho [4]). Animal species with low population levels are more likely to be driven to extinction by nuclear winter and anthropogenic environmental perturbations than by a nuclear winter alone. Additionally, the extinction percentages of marine animals and terrestrial tetrapods have been predicted when a nuclear war could occur in conjunction with anthropogenic environmental perturbations.

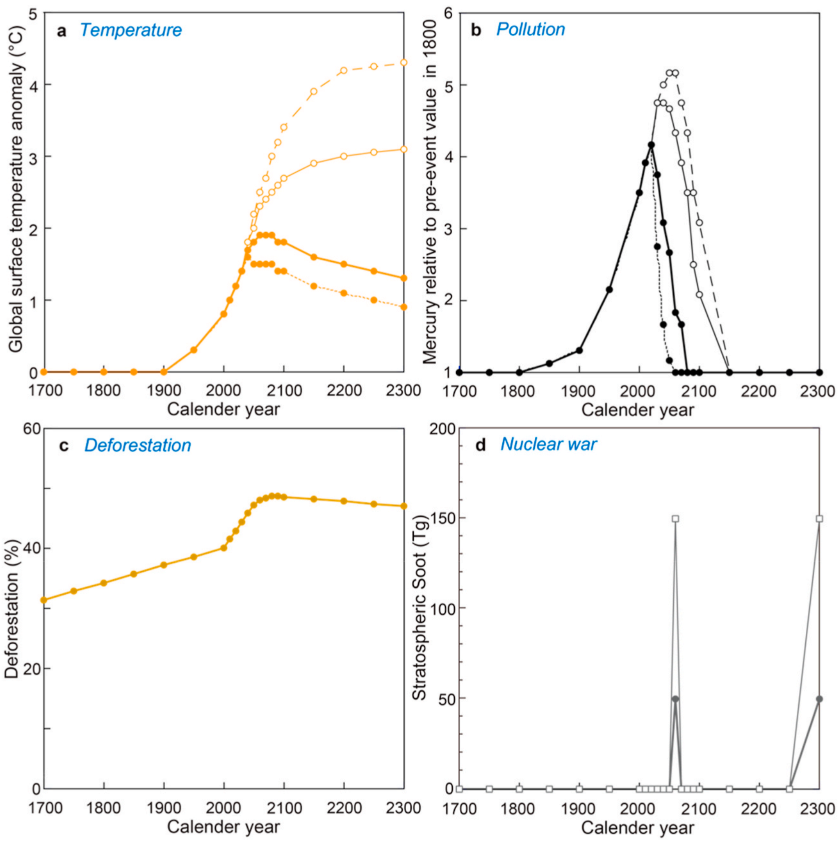

Fig. 1. Changes in global surface temperature anomalies (a) [12], mercury concentrations (relative to 1800 CE) as a proxy for pollution (b), deforestation area percentages (relative to 4000 BCE) (c), and amounts of stratospheric soot introduced by nuclear war, which would reduce sunlight penetration and induce global cooling (d) [11] from 1700 to 2300 CE. The four curves for global warming and pollution correspond to SSP1-1.9, SSP1-2.6, SSP2-4.5, and SSP4-6.0 (the 21st century scenarios simulated by the Scenario Model Intercomparison Project [ScenarioMIP]), respectively [12,13], (**a**, **b**). Dotted lines: SSP1-1.9. Thick lines: SSP1-2.6. Thin lines: SSP2-4.5. Dashed lines: SSP4-6.0. A nuclear war is simulated in 2060 and 2300 (**d**). These data are shown in Supplementary Table A2 (for **a–c**).

In this paper, more precise analyses, such as improved calculation methods and analyses of 10-year intervals between 2000 and 2100 and 50-year intervals between 1700 and 2300 instead of the 100-year interval analyses of Kaiho [4], were conducted. The novelties of this study involve determining (i) the timing of the greatest animal extinction magnitudes, (ii) the effect of a nuclear war during anthropogenic environmental perturbations and (iii) a prioritization of environmental causes of extinctions to decrease animal species loss.

2. Materials and Methods

2.1. Procedure

First, cause–extinction models were selected based on Phanerozoic data and climate scenarios to calculate causal proxies and extinction percentages (Supplementary Fig. A1, Supplementary Table A1). Second, causal proxy values (global warming, pollution, deforestation, and stratospheric soot amount released by nuclear war) during 1700–2300 were calculated (Fig. 1, Supplementary Table A2). Third, potential extinction percentages based on each extinction cause for marine and terrestrial tetrapod animals from 1700 to 2300 CE were obtained using the data from Supplementary Tables A1 and A2 (Supplementary Fig. A2, Supplementary Table A3). Finally, marine and terrestrial tetrapod animal extinction percentages were calculated for all four extinction causes at the four sets of contribution rates for pollution and deforestation (Fig. 2, Supplementary Tables A4 and A5). All calculations for global warming and pollution were conducted under the SSP1-1.9, SSP1-2.6, SSP2-4.5, and SSP4-6.0 climate scenarios for the 21st century from the Scenario Model Intercomparison Project (ScenarioMIP) [12,13].

The four climate scenarios coupled with the four sets of contribution rates of pollution and deforestation accompanied by two nuclear war scenarios cover all possible resulting extinction percentages to provide an accurate prediction of future crisis magnitudes.

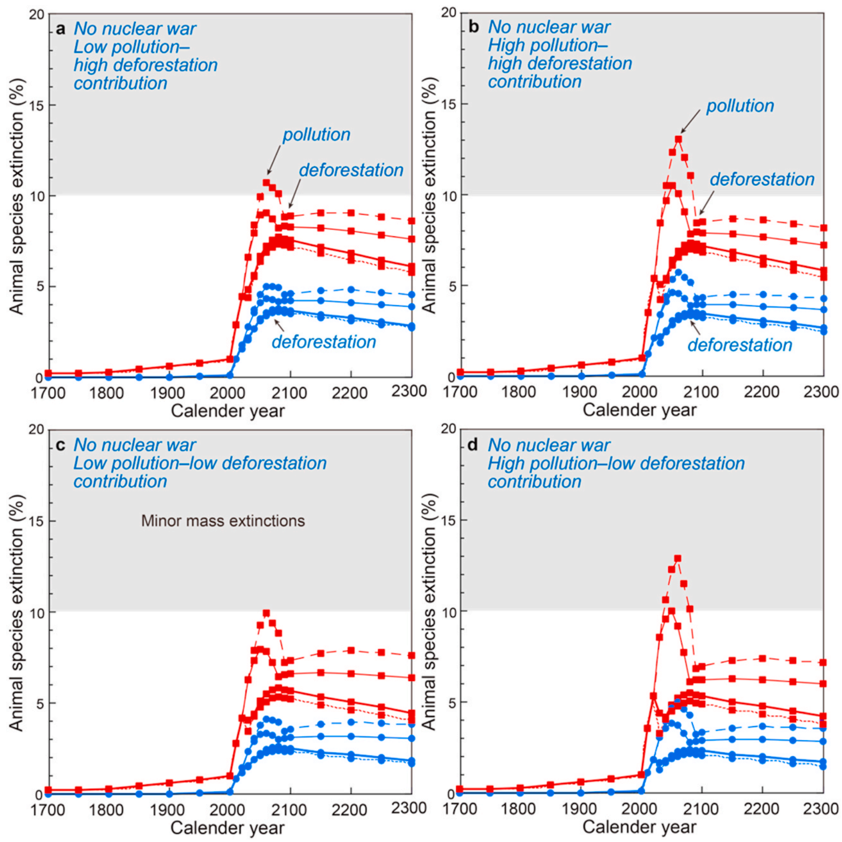

Fig. 2. Animal species extinction percentages in the marine (blue circle) and terrestrial (tetrapods, red square) environments from 1700 to 2300 CE under four causal contribution rate sets, four CO_2 emission scenarios, and no nuclear war. See Materials and Methods on contribution rates and extinction percentages. Dotted lines: SSP1-1.9. Thick lines: SSP1-2.6. Thin lines: SSP2-4.5. Dashed lines: SSP4-6.0. The final species extinction percentage in each figure is thought to be similar to the maximum species extinction percentage or slightly higher. These data are shown in Supplementary Tables A4 and A5. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.2. Cause–extinction model based on Phanerozoic data

For the cause–extinction global warming model, the relationship between global warming and extinction percentages was used based on the Paleocene–Eocene Thermal Maximum (PETM) because it involves conditions similar to current environmental changes and it lacks significant global cooling [4,15] (Supplementary Fig. A1a). For the cause–extinction pollution model, past Hg/total organic carbon (TOC) values were used [4] (Supplementary Fig. A1b). For the cause–extinction deforestation model, the lack of tree fossils after the largest mass extinction at the end of the Permian was used [4] (Supplementary Fig. A1c).

Soot amounts were calculated from three impact craters (Chicxulub, Morokweng, and Popigai) using the methods in Kaiho and Oshima [16] to construct Supplementary Fig. A1. The amount of soot in the global stratosphere was estimated as the product of the volume (km^3) of combustible rocks, the specific gravity of soot, a scaling factor to convert from Gt to Tg, TOC content, the soot emission factor, and the surviving fraction. The specific gravity of soot was 2.3. A scaling factor of 1000 was used to convert from Gt to Tg. TOC was 0.001 for oceanic sedimentary rocks, 0.005 and 0.003 for continental sedimentary rocks (0.005 for carbonates and mudstones and 0.003 for predominant carbonates), and 0.000 for deep seawater, crust, and mantle material. The soot emission factor was 0.065, and the surviving fraction was 0.068–0.118. The amount of soot ejected from the Chicxulub crater was 350–610 Tg black carbon (BC), which corresponds to 10–12 °C of global surface cooling [15,16] and 68% and 67% extinction percentages among marine animals and terrestrial tetrapods, respectively [4,16] (Supplementary Fig. A1d). The maximum monthly global mean surface air temperature anomalies caused by stratospheric soot were obtained from Fig. 5 of Kaiho and Oshima [16].

2.3. Changes in causal proxy values

Global surface temperature anomaly data between 1700 and 2100 were obtained from the literature related to the International Panel on Climate Change (IPCC) [12,13], while the data between 2100 and 2300 were obtained directly from an IPPC report [14].

Past pollution levels were estimated based on the mercury (Hg) content (maximum value during an event divided by averaged pre-event value) in sediments from 1700 to 2010 [17,18]. The future Hg rate (from 2010 to 2300) was calculated from predicted CO_2 emissions because CO_2 emissions released from fossil fuels accompany Hg emissions [19] and can be expressed using the formula in Appendix A (Fig. 1b).

For the calculation of the deforestation percentages, a 40% forest loss between 4000 BCE and 2000 CE and a 5.4% forest loss (%) between 1990 and 2005 [20] were used to calculate forest loss (%) between 1700 and 2050. Future deforestation percentages from 2060 to 2300 were calculated based on the relationship between deforestation and human population totals [20–22]. The equations are shown inAppendix A.

Stratospheric soot amounts in the minor and major nuclear war cases were set at 50 and 150 Tg BC (i.e., soot) based on data from Coupe et al. [11] (Fig. 1d).

2.4. Potential extinction rate related to each extinction cause

The following formula was used to obtain potential extinction rate values (not real extinction percentages except for the case of nuclear war) for each dependent cause (Fig. 2, Supplementary Table A3). The general equation for potential extinction (PE) percentages is the following: PE = pre-PE + (maximum-PE – pre-PE) x (index-value in the year – preindex-value)/(maximum-index-value – preindex-value). Specific equations for each cause are shown in Appendix A.

2.5. Extinction contribution rates

The PETM that occurred 55 million years ago and was induced by ocean-ridge volcanism is the best scenario for estimating the effect of global warming on the magnitude of an extinction event because the 6.5 °C of global warming that occurred during the PETM was not accompanied by significant global cooling, pollution, deforestation, or mass extinctions [4]. Therefore, the PETM was used to estimate the magnitude of extinctions driven exclusively by global warming. In addition, climate change affects animals globally. Therefore, the contribution rate of climate change to animal extinctions was 1. Because pollution affects local populations, some animals can escape; therefore, the contribution rate of pollution was set to 0.1 or 0.2. The effect of deforestation on terrestrial animals should be as high as that of deforestation on animal species occupancy, and 80–90% of terrestrial species inhabit forests. Therefore, the contribution rate of deforestation to extinction was set at 0.8 for terrestrial animals as a high contribution percentage. A value of 0.4 was used for the low deforestation contribution rate. Tree leaves are the main source of nutrition in the marine realm and control the diversity of marine animals. Therefore, deforestation is an important factor when assessing the extinction magnitude of marine animals. Based on the high contribution of forests to marine animals, the contribution rate of deforestation to marine animal extinction was set to 0.2 and 0.4. Nuclear war independently causes animal extinctions.

Using these contribution percentages, the extinction percentage (E) values presented in this study were calculated. The formulas are shown in Appendix A.

2.6. Contribution percentages of each cause

The contribution percentages of each cause (global warming, pollution, and deforestation) for animal species extinctions during 2000–2300 CE were calculated using potential extinction rates dependent on each cause. The formulas are shown in Appendix A.

3. Results

3.1. Extinction magnitude based on anthropogenic perturbations without nuclear war

Global surface temperatures are increasing and, under low CO_2 emission scenarios, will continue to increase until the middle of this century. However, under the medium CO_2 emission scenarios, temperatures will continue to rise until 2300, although CO_2 emissions will decrease from 2030 to 2050 [12] (Fig. 1a). A pollution spike will occur in 2020 under the low CO_2 emission scenarios and in 2030–2050 under the medium CO_2 emission scenarios, whereas the deforestation maxima will occur in 2070–2100 (Fig. 1b and c).

Species extinction rates were obtained for marine animals and terrestrial tetrapod animals from 1700 to 2300 at four causal contribution rates and under the four climate scenarios (4 × 4 case analyses), which likely encompass all potential scenarios (Fig. 2 made from Supplementary Figs. A1, A2 and Fig. 1, see Materials and Methods). The results showed that the extinction rate will rapidly increase from 2000, peak in 2060–2080, and then decrease but staying high. The extinction rate will be 5–8% for terrestrial tetrapods and 2–4% for marine animal species as maxima in 2080 under the low CO_2 emission scenarios. However, under the medium CO_2 emission scenarios, a shorter spike in extinctions will start in 2000, and extinctions will reach their maxima in 2060. This will result in losses of 8–13% for terrestrial tetrapods and 3–6% for marine animals by 2060 (Fig. 2).

The degree that each extinction cause contributed to the extinctions was analyzed. The results showed that the main causes of extinction were initially pollution and deforestation; however, this will eventually change to deforestation for both marine and terrestrial animals. The timing of the change was 2030 and 2070 under the low and medium CO_2 emission scenarios, respectively (Fig. 3, Supplementary Fig. A3). Global warming will be a primary contributor to extinction during 2090–2300 under the medium CO_2 emission scenarios.

3.2. Extinction magnitude based on nuclear war occurring in conjunction with anthropogenic perturbations

Nuclear war and its associated impacts will reduce sunlight and cause global cooling, which will induce deforestation [23] and mass extinction [4,7,23]. Extinction magnitudes were calculated by considering stratospheric soot levels of 50 and 150 Tg BC (soot;

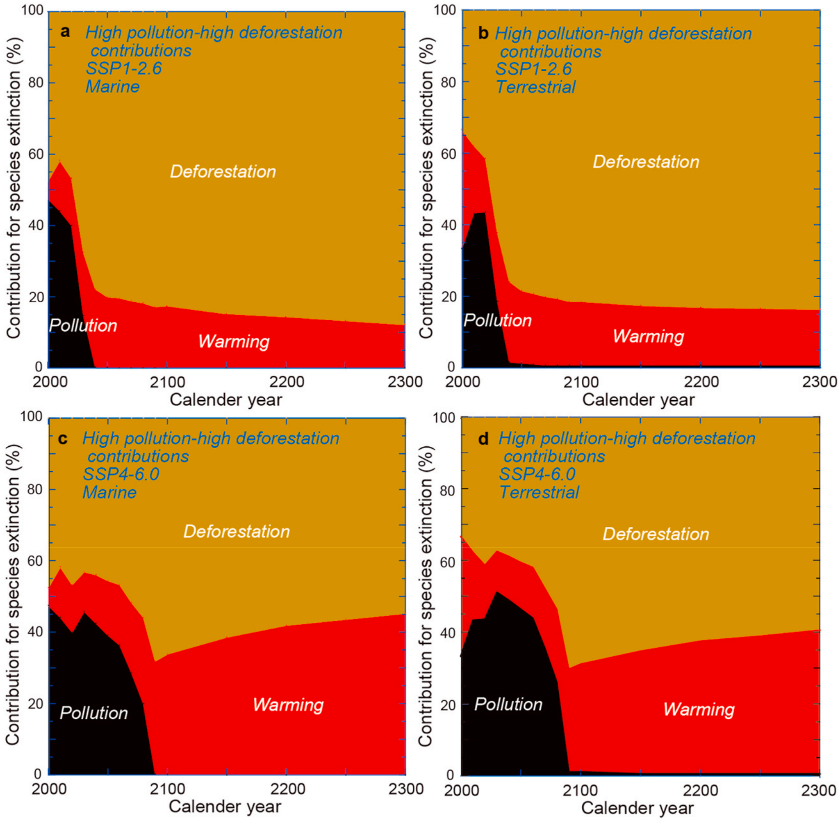

Fig. 3. Animal species extinction contribution rates (global warming, pollution, and deforestation) for animal extinctions during 2000–2300 CE under a no nuclear war scenario. Marine animals under SSP1-2.6 (**a**). Terrestrial tetrapods under SSP1-2.6 (**b**). Marine animals under SSP4-6.0 (**c**). Terrestrial tetrapods under SSP4-6.0 (**d**). Figures **a**–**d** correspond to the contribution rates in Fig. 2**b** (high pollution and high deforestation contributions). These data are shown in Supplementary Table A6. Figures for the four extinction cause contribution sets are shown in Supplementary Fig. A3 and Supplementary Tables A6–A9.

Fig. 1d). These values are reflective of the total proliferation of urban fires during minor (India and Pakistan) and major (USA and Russia) nuclear conflicts [10,11]. Stratospheric soot amounts and global surface temperature anomalies were recalculated from three impact craters. At Morokweng (which represents the Jurassic–Cretaceous [J–K] boundary) and Popigai (the late Eocene), the results showed 50–90 Tg BC and 120–220 Tg BC and 3.5–5 °C and 5.5–8 °C of cooling, respectively. The corresponding extinction percentages for the Popigai impact were 4% for marine animal species and 8% for terrestrial tetrapods, and for the Morokweng impact, extinction percentages were 43% for marine animal species and 58% for terrestrial tetrapods (Supplementary Table 1, Supplementary Fig. A1d) [4,24]. Using these data with the known data of the Chicxulub impact, a minor nuclear war (50 Tg BC) will cause 3.5 °C of global cooling, a 0–4% (2% on average) loss in marine animal species and a 0–8% (4% on average) loss in terrestrial tetrapods, whereas a major nuclear war (150 Tg BC) will induce 6.5 °C of global cooling and lead to losses in marine animals and terrestrial tetrapods of 20–45% (33% on average) and 30–60% (45% on average), respectively, as shown in Supplementary Fig. A1d. The average values with the errors are used in Supplementary Fig. A2d.

If nuclear conflicts were to occur in 2060, coincident with the anthropogenic perturbation maxima, then a minor nuclear war (under low CO_2 emission scenarios) would cause a loss of 9–11% for terrestrial tetrapod species and 4–6% for marine animals (Fig. 4a). A minor nuclear war under medium CO_2 emissions will cause a loss of 12–17% for terrestrial tetrapod species and 5–8% for marine animal species. However, a major nuclear war would lead to the extinction of 50–52% (±15%) of terrestrial tetrapod species and 35–37% (±13%) of marine animal species under the low CO_2 emission scenario. If a major nuclear war occurred during the medium CO_2 emission scenario, terrestrial tetrapod species and marine animals would experience losses of 53–58% (±15%) and 36–39% (±13%), respectively (Fig. 4a). These values are thought to be the maxima, and actual losses would be lower because this study does not consider the potential decrease in stratospheric soot due to the interception of nuclear weapons.

If a nuclear war were to occur in 2300, approximately 200 years after the anthropogenic perturbation maxima, then the calculation results indicate that the extinction percentages would be similar to the theoretical losses from the 2060 CE major nuclear war scenario (Fig. 4b).

4. Discussion

4.1. *What will occur in the near future without nuclear war*

If humans reduce greenhouse gas emissions, pollution, and deforestation and do not start nuclear wars, then a 5–8% loss in terrestrial animal species will occur in 2080 CE. However, when no decreases in greenhouse gas emissions and no nuclear war were modeled, this loss increased to an 8–13% loss in animal species in 2060 CE. These latter values are similar to an approximately 10% loss in species of mammalian species during 2000–2100 CE using an extinction rate [8] and in mammals, birds, and reptiles by removing the species with a higher risk of extinction [9]. The timing of the extinction maximum is consistent with that of Spalding and Hull [25] as the assumption and Kaiho [4] as a calculation result at approximately 2100 CE. This paper provides more precise timelines, 2060–2080 CE, as the peak age of the animal crisis. The extinction percentages under a scenario of no nuclear war are still approximately ten times higher than the present extinction percentages (<1% for marine animals and 1% for terrestrial tetrapods in 2010 CE [1,2]). The extinction percentages will reach neither a minor nor major mass extinction level (defined as >10% and >60% for marine animal species loss, respectively [4,7]). However, the accompanying environmental changes are severe for humans. These changes will likely induce environmental disasters, especially on land, a significant food shortage, and an increase in sea level, which

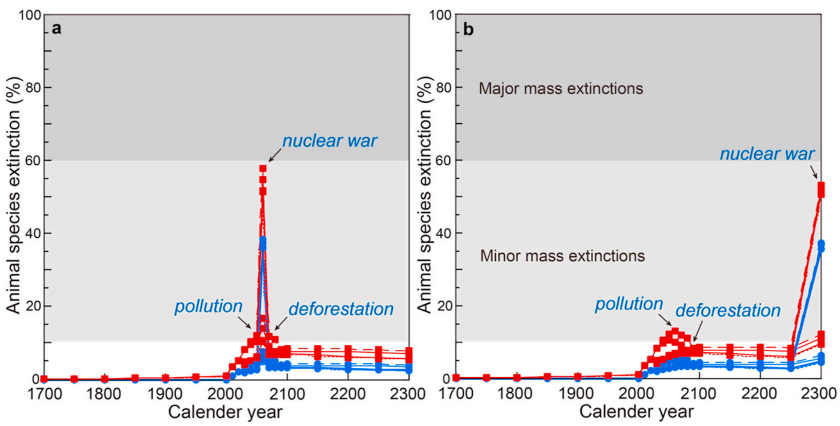

Fig. 4. Animal species extinction percentages in the marine (blue circle) and terrestrial (tetrapods, red square) environments from 1700 to 2300 CE under four CO_2 emission scenarios and two different nuclear war magnitudes on two different dates for the high extinction contribution rates of pollution and deforestation. A nuclear war is simulated in 2060 (a) and 2300 (b). Dotted lines: SSP1-1.9. Thick lines: SSP1-2.6. Thin lines: SSP2-4.5. Dashed lines: SSP4-6.0. These data are shown in Supplementary Tables A4, A5, and A10. Extinction percentages during a major nuclear war include a ±13% error for marine animals and a ±15% error for terrestrial tetrapods shown in Supplementary Fig. A2d. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

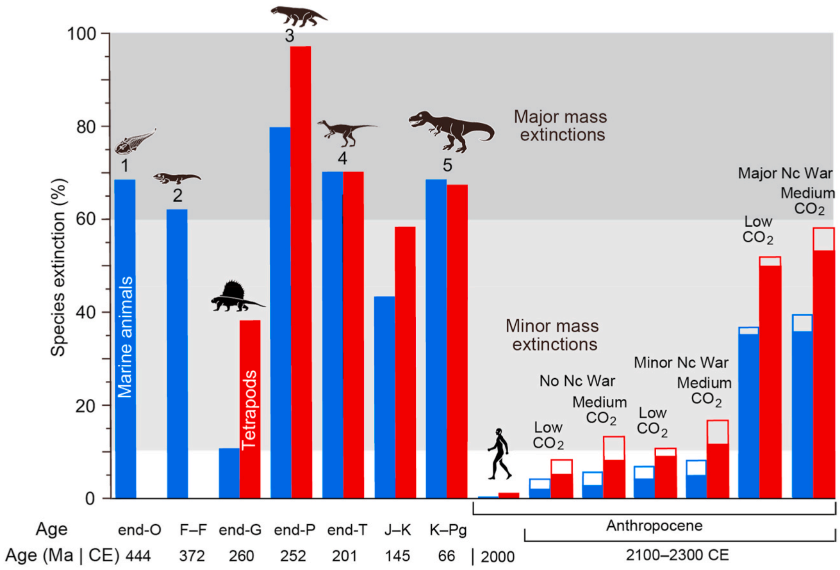

Fig. 5. Comparison between extinction percentages in the Phanerozoic mass extinctions and current Anthropocene animal crisis. Numbers 1 to 5: the five major mass extinctions. Closed bars in the Anthropocene show minimum values. Hollow bars in the Anthropocene show maximum values. The variations are due to different extinction contribution rates of pollution and deforestation (Supplementary Tables A10–12). O: Ordovician. F–F: Frasnian–Famennian boundary. G: Guadalupian. P: Permian. T: Triassic. J–K: Jurassic–Cretaceous boundary. K–Pg: Cretaceous–Paleogene boundary. Nc war: nuclear war case. Each silhouette shows a representative vertebrate animal from each age. These data in geological ages are shown in Kaiho [4,7]. These data in the Anthropocene are shown in Supplementary Table A12. Extinction percentages during a major nuclear war include a ±13% error for marine animals and a ±15% error for terrestrial tetrapods shown in Supplementary Fig. A2d.

could lead to a decrease in the human population. These events may disturb human social systems and alter human relationships with the environment.

Human conduct will be the deciding factor for which of the four temperature anomalies and pollution curves shown in each panel of Fig. 1a and b and 2 occur. Under the low CO_2 emission scenarios, we will prevent the early extinction spike, resulting in lower extinction percentages and a delay in the extinction maxima (Fig. 2). Most extinctions will persist until 2100 under the low CO_2 emission scenarios and until 2100–2200 under the medium CO_2 emission scenarios because most low-tolerance animals could be lost by those years in each scenario.

Pollution is the main cause of extinctions when (i) CO_2 emissions increase because CO_2 emissions are increasing in parallel with toxic gas and halogen gas, which causes ozone depletion, and when (ii) there is an increase in industrial products [3,19,26]. After a decrease in CO_2 emissions, deforestation will replace pollution as the main cause of animal extinctions because the CO_2 emission maximum accompanied by pollutant emission peaks [3] will be followed by the human population maximum [27,28], which would occur in parallel with increasing rates of deforestation [21,22] (Fig. 1b and c). Global warming will be the main extinction cause following the deforestation maximum in 2090 under medium CO_2 emissions. However, by this point, extinctions would be primarily complete.

Most animals and plants can migrate to cooler areas and survive during an increase in global temperatures of less than 6.5 °C. This basis for this information is the PETM temperature anomaly, during which no mass extinctions occurred but a benthic crisis in the deep sea occurred [4]. Therefore, individually, global warming contributes minimally to animal extinctions. However, modern pollution (3.5 Hg rate) and modern 40% rates of deforestation exceed the those during the PETM (3.0 Hg rate and 0% deforestation [29]). Therefore, the cause–extinction model [4] was used based on mass extinction data in this study. Since pollution or deforestation or global warming cannot explain all extinctions, a coupling effect of these three causes was used to calculate extinction percentages (see Materials and Methods).

4.2. Distinct issues related to a major nuclear war occurring during environmental perturbations

Anthropogenic environmental perturbations will cause not only approximately 5–10% of animal extinctions but also a significant decrease in the population of each animal species. It is essential that each species sustain a minimum of hundreds of individuals in an area of activity to retain a sustainable breeding population. Decreasing populations will results in animal extinctions being more likely to occur in the decades ahead. Based on this scenario, the calculation results indicate that the extinction percentages, considering anthropogenic environmental perturbations, could be approximately as high as 45–50% (the average of marine and terrestrial animal species losses including ± 13–15% error shown in Supplementary Fig. A2d), which is ~10% higher than those calculated for the major nuclear war case that does not consider anthropogenic environmental perturbations.

When a major nuclear war occurs during a period of anthropogenic environmental perturbations, the extinction percentages will be

~50% higher compared with those during the no nuclear war case, but these values will not reach a minor mass extinction level (Fig. 5). A major nuclear war that occurring at the same time as anthropogenic environmental perturbations could induce a minor mass extinction event, such as the mass extinction event that occurred at the J–K boundary [4] (Fig. 5).

4.3. What is recommended to prevent the anthropogenic crisis?

The environmental changes shown in Fig. 1a–c serve as useful information for developing environmental protection measures. To prevent the first spike of extinctions during 2020–2060 (Fig. 2), anthropogenic toxic gas emissions, microplastic debris [30], and forest loss should be reduced as quickly as possible. To maintain low extinction percentages, we should protect forests and recover lost forests. To prevent large disasters related to floods, strong storms, and changes in sea level, CO_2 emissions should be reduced as quickly as possible. Furthermore, preventing nuclear war is essential to averting mass extinctions and significantly decreasing the human population.

Between 1990 and 2005, high rates of forest loss occurred in tropical–subtropical domains (7.1–4.0%), and low rates of forest loss occurred in temperate–boreal domains (1.6–1.2%) [20,31], accounting for a total loss of 5.4%. Tropical forests with high animal and plant diversity (80–90% occupation) are critical to preventing animal extinctions. If humans can maintain the 2030 deforestation rate between 2030 and 2090, then the percentage of deforestation will decrease in accordance with a decrease in human population starting in 2100, and terrestrial extinction percentages will decrease by approximately 20% compared with the most likely cases (Supplementary Table A17). If humans can maintain the percentage of deforestation observed in 2000 after 2030, as an ideal measure for deforestation, then terrestrial extinction percentages will decrease by approximately 30% compared with the most likely case (Supplementary Table A18).

Although extinction-risk assessments play a major role in prioritizing conservation action at national and international levels [32], there has been no prioritization process used to prevent the environmental causes of extinctions to decrease animal species loss. This study shows that the conservation priority for animal species is to prevent nuclear war, reduce deforestation rates, decrease pollution, and limit global warming. The importance of deforestation and land conservation are supported by a study showing the importance of land conservation in terms of reducing the tropical extinction risk [33]. Decreasing pollution is thought to be especially important for freshwater fish survival. These are all crucial tasks for human society since they are necessary steps that benefit humans, animals, and their environments on Earth. Humans are causing the environmental–animal crisis; therefore, humans are responsible for averting the crisis.

5. Conclusion and policy recommendations

This research shows that anthropogenic environmental perturbations will drive $4 \pm 2\%$ of marine animal species and $9 \pm 4\%$ of terrestrial tetrapod species to extinction during 2060–2080 CE. Furthermore, a major nuclear war concurrent with environmental perturbations will lead to at most a ~40% loss in marine animal species and ~60% loss in terrestrial tetrapod species. Assuming no nuclear war, 2–4% and 5–8% of these marine and terrestrial tetrapod species extinctions will occur in 2080 under low anthropogenic CO_2 emission scenarios (causing 1.8 °C of global warming above preindustrial levels), respectively, and under medium anthropogenic CO_2 emission scenarios (causing 3 °C of global warming until 2100), 3–6% and 8–13% of these extinctions will occur by 2060. The main causes of these extinctions will first be pollution and deforestation. However, these causes will change deforestation in 2030 (2070) under the low (medium) CO_2 emission scenarios. Eventually, global warming and deforestation will become the primary causes of extinction after 2090 under medium CO_2 emissions. When nuclear war concurrent with environmental perturbations occur, four causes, inducing past mass extinctions, will be present. The environments formed by three causes, excluding nuclear war, largely differ from the environments during the past mass extinctions. This difference is reflected by the low extinction magnitude under the no nuclear war case.

These results have urgent implications for averting significant animal extinctions in the near future. Humans should focus on (i) implementing the CO_2 reductions put in place by current governments globally, (ii) stopping pollution, (iii) stopping deforestation, and (iv) preventing nuclear war to prevent a higher-magnitude crisis [4]. In particular, stopping deforestation and preventing nuclear war are essential for maintaining ecological balance, these events have a greater effect on animal species loss than pollution and warming during the maxima of animal species loss in the late 21st century. Failure to stop these four extinction causes will lead to a significant decrease in biodiversity and the collapse of ecological balance, resulting in a significant decrease in food and the human population. Therefore, implementing the above measures will benefit humans. Targeted recovery actions for threatened species are also required to avert human-induced extinctions [34,35]. The magnitude of Anthropocene extinctions will not reach the sixth mass extinction level but will reach a minor mass extinction level at most under an intermediate nuclear war level that is between minor and major nuclear war levels, thus more than a nineth mass extinction including minor mass extinctions (Devonian–Carboniferous boundary, Guadalupian–Lopingian boundary, and Jurassic–Cretaceous boundary).

The main limitation of this study is the uncertainty of the effects of nuclear war because the probability of hitting targets is uncertain, and the species loss percentages are thought to be at a maximum. Another limitation of this study is the uncertainty of the species loss percentage for the low-magnitude mass extinctions because well-known mass extinctions are major mass extinctions; thus, there is minimal data on minor mass extinctions. Finally, limitations of future recommendations involve the difficulty in balancing protection of Earth environments and maintaining human society and its linked economy, culture, food, and population. Therefore, the next stage of future crisis studies should focus on measures to protect the Earth's environment while maintaining human society, which are currently discussed in world politics.

The extinction peak will occur in 40 to 60 years during the next generation; therefore, humans must develop countermeasures soon to avert the predicted crisis. This paper provides fundamental data for developing countermeasures.

Author contribution statement

Kunio Kaiho: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

All data is available in the main text or the supplementary materials.

Declaration of interest's statement

The authors declare no conflict of interest.

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Appendix A. Supplementary data

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Further reading

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