Author replies for reviewer comments

This document contains a point by point reply to the issues raised by the reviewers (in red); changes made in the MS are indicated in blue. All original comments by the reviewers are left in black font.

1. Author replies for comments from reviewer 1

Summary

In this research article, Kunio Kaiho presents novel findings on the future development of metazoan diversity in superterranean, subterranean, surface-water, and deep-water habitats based on diversity changes in the past. By incorporating seven different environmental drivers, the author projects the com-plete extinction of metazoans within the next 700 million years, which is 300–400 million years earlier than previously estimated.

General comments

Overall, the manuscript is well written and provides novel insights into an important field of research. The language is almost perfect, clear, and easy to follow. However, there are a few general points that should be addressed before final publication of the article.

Neither the Introduction nor the Discussion provides much context regarding previous research efforts. While the Introduction nicely explains the different environmental drivers incorporated into the current study, it is unclear what previous research entailed and what the current study adds to it. These aspects should be included in the revised manuscript.

Author Reply: Added in the Introduction. Estimates published after 2010 for the eventual collapse of Earth's biosphere vary widely. Projections based solely on long-term solar-driven warming range from 1.0 to 5.0 Gyr (O'Malley-James et al., 2012; Rushby, 2013; Leconte et al., 2013; Wolf and Toon, 2015). In contrast, CO_2-depletion models predict substantially earlier biosphere loss at 0.84–1.08 Gyr (Rushby, 2015; Ozaki and Reinhard, 2021). Mello and Friaça (2019) argue that thermal limits may delay biosphere collapse to ~1.5 Gyr, whereas atmospheric O_2 is projected to fall to 1% PAL within 1.08 ± 0.14 Gyr, potentially driving an earlier extinction of metazoans (Ozaki and Reinhard, 2021). Overall, current geosphere–biosphere models suggest a remaining biosphere lifespan of at least ~0.8 Gyr, with ~1.2 Gyr as a plausible median estimate (Jebari and Sandberg, 2022).

Similarly, the Discussion repeats the major results of the current study without discussing them in the context of previous findings. For example, it is repeatedly mentioned throughout the manuscript that the current study projects metazoan extinction to occur 300–400 million years earlier than previous estimates, but these previous estimates are not further specified. What differences between previous studies and the current study may cause these different results? Why are the results of the current study more/similarly realistic? These questions should be addressed in the Discussion.

Author Reply: Added in the Discussion.

4.1 Characteristics of future diversity estimation in this study

A remaining biosphere lifespan of ~1.2 Gyr has been proposed as a plausible median estimate (Jebari and Sandberg, 2022). When only the long-term warming trend driven by gradually increasing solar luminosity is considered (Mello and Friaça, 2019), metazoans go extinct at Event 14 at ~1.3 Gyr for marine taxa and Event 13 at ~1.2 Gyr for terrestrial taxa, based on the intersection of the black dashed line with the upper boundary of GATES90 following the logic in Section 3.2 (Fig. 2). Under the oxygen-depletion scenario of Ozaki and Reinhard (2021), atmospheric O_2 falls below ~0.01 PAL at ~1.1 Gyr—sufficient to induce metazoan extinction. The present study indicates that metazoan demise occurs 0.1 Gyr earlier than estimates based solely on long-term warming and accompanied atmospheric O_2 and CO_2 loss, except for marine metazoans under the Evolutional Model.

In addition, I think that some parts of the Methods section are difficult to follow. Firstly, this section uses many abbreviations, but not all of them are defined in the text itself, only in figure/table captions (e.g., PAL is only defined in the caption of Fig. 1). Secondly, many terms are unclear to the reader and require further explanation (e.g., what exactly are diversity rates and what is the difference between survival rates and survival area rates?). Thirdly, the argumentation is partly difficult to follow since the required explanations are either insufficient or provided later in the Results or Discussion section. I recommend adding further explanations and revising the structure of the manuscript where necessary. I give specific examples in the “Specific comments” section.

Author Reply: Added Table 3 to explain abbreviations. Revised the structure of the method section largely.

Specific comments

• _L. 29: I would replace “all known forms of life” by “**almost** all known forms of life”, e.g., tardigrades can survive temperatures higher than 100°C.

Author Reply: Done

• _L. 32: Can you shortly explain what C3 and C4 plants are?

Author Reply: Revised to “C This warming accelerates continental weathering, which removes atmospheric CO_2 over timescales of hundreds of thousands of years, triggering cascading biological crises. Declining CO_2 will differentially affect C_3 and C_4 plants because of their distinct photosynthetic pathways: C_4 plants tolerate hotter, drier, low-CO_2 conditions better than C_3 plants. Thus, C_3 plants (including most trees) are expected to decline first, followed by C_4 plants, ultimately leading to collapse of metazoan ecosystems (Reinfelder et al., 2000, 2004; Mello and Friaça, 2019; Ozaki and Reinhard, 2021)."

• _L. 52-53: This sentence disrupts the flow of the text. Since the corresponding information was just mentioned a few paragraphs earlier, the sentence is not necessary in my opinion.

Author Reply: Removed the sentence: ~~As solar luminosity increases, intensified weathering will reduce atmospheric CO_2, initiating crises for C3 plants, then C4 plants.~~

• _L. 95: "These data are applied in section 2.2." – The current section is 2.2, so I do not understand this sentence.

Author Reply: Removed the words "Subsection 2.2"

• _Section 2.3: Are only records of marine metazoans available? If yes, the possible impacts of this limitation should be discussed.

Author Reply: Added "and terrestrial" in L132.

• _L. 97: What exactly is meant by "diversity rates"?

Author Reply: Revised to "Projections of future atmospheric O_2 levels and marine and terrestrial biodiversity were guided by patterns observed during the Paleozoic biodiversity maximum." in L132.

• _L. 98: What is PAL?

Author Reply: Revsied to "present atmospheric levels (PAL)" in Introduction.

• _L 106-107: I think you mean that oxygen levels drop in the habitats of metazoans and not in metazoans themselves, right?

Author Reply: Removed ", with significant declines occurring when oxygen levels drop in both marine and terrestrial metazoans" Used "atmospheric O_2 levels" in L.138

• _L. 108: Why do terrestrial metazoans require an ozone layer for evolutionary adaptation? (This is explained in l. 491-493, but I would already explain it here).

Author Reply: Revised the sentence to: Major drivers of past mass extinctions include global cooling, global warming, ozone-layer destruction that exposes organisms to harmful short-wavelength UV radiation, ocean acidification, and widespread oceanic anoxia. in L. 305.

• _L. 110-115: What were the main reasons for mass extinction during these events?

Author Reply: In Introduction: In addition, Earth's climate has repeatedly experienced abrupt perturbations. Large-scale volcanism and asteroid impacts have induced rapid global cooling followed by long-term warming (Kaiho, 2025), triggering mass extinctions throughout the past 500 Myr (Erwin et al., 1987; Sepkoski, 1996; Bambach, 2006; Kaiho, 2022). In subsection 2.5: Major drivers of past mass extinctions include global cooling, global warming, ozone-layer destruction that exposes organisms to harmful short-wavelength UV radiation, ocean acidification, and widespread oceanic anoxia. L305.

• _L. 131: There is no red curve in Fig. 1. Do you mean the orange curve?

Author Reply: Yes, I revised it to orange curve.

• _L. 147: Which were the five largest mass extinction events?

Author Reply: I selected the five major mass extinctions, each marked by abrupt environmental disruption and >35% marine genera loss—equivalent to >60% species extinction—based on Bambach (2006) and Kaiho (2022). Family-level extinction percentages capture severe biodiversity losses across taxa. Marine metazoan family-level extinctions were ~22% (end-Ordovician), 21% (Late Devonian), 50% (end-Permian), 20% (end-Triassic), and 15% (end-Cretaceous) (Sepkoski, 1982). L.116.

• _L. 152: I thought ΔTec was estimated using SST data as stated in the previous section?

Author Reply: Yes, it was. Now I use ΔTe [cooling cases] in L. 195.

• _L. 163: What is sill?

Author Reply: Revised to "initial sill (a tabular sheet intrusion from magma) temperature" L203.

• _L. 167-168: How are long-term changes in CO2 and SO2 emissions related to short-term temperature anomalies?

Author Reply: This sentence does not refer to long-term trends, but rather to abrupt changes that trigger major mass extinctions. I applied a gradual decrease in mantle temperature to estimate future SO_2 and CO_2 emission rates relative to present-day levels. These rates were then used to calculate extinction percentages. See Table A2.

• _L. 191: Why do you use regions with oceanic climate?

Author Reply: Revised to "Oceanic climate regions on land were used as reference points because they experience milder and more stable climates than continental interiors." L289.

• _L. 196: Does a gradient of 15°C only apply to warm conditions or why do you explicitly mention warm conditions here?

Author Reply: Revised to "5. Establishing warm-Earth latitudinal temperature gradients

The warm-Earth latitudinal gradient of LAT was set to be 20 °C and 14 °C larger than the corresponding sea-surface temperature (SST) gradients of 17 °C and 11 °C from 0° to 90° latitude when GAT is 30 °C and 40 °C, respectively (thin oblique lines in Fig. 4a; Gaskella et al., 2022). These gradients reflect changes in solar incidence associated with Earth's axial tilt." L247.

• _L. 199: Where exactly do the 5°C come from?

Author Reply: Revised to 3°C. "3. Conversion from LDMT to Local Monthly Maximum Temperature (LMMT)

A –3 °C correction was applied to convert LDMT to LMMT. This offset reflects the typical difference between monthly mean and daily maximum temperatures during the warmest month, based on observations from coastal cities including Singapore (~0° N), Shanghai (~30° N), Helsinki (~60° N), and Longyearbyen (~80° N) (Weather Spark)." L238.

- _L. 201: Same as l. 191 and l. 196: Why do you use data from warm coastal cities?

Author Reply: Delete "warm" resulting in "coastal cities". 4. Conversion from LMMT to Local Annual Temperature (LAT)

LAT was derived by applying a latitudinally dependent correction (ΔLT; Fig. 4).

ΔLT values were set to –2 °C, –3.5 °C, –7.5 °C, and –9 °C for ~0°, ~30°, ~60°, and ~80° N, respectively, following temperature differences observed in coastal cities of the eastern Atlantic (Weather Spark). L243.

- _L. 207: There is no section 2.3.3. Do you mean 2.6.3?

Author Reply: Yes, it was 2.6.3, but now it is revised (Section 2.4.1).

- _Equation 11: What is ΔLT? (LT is only defined in the caption of Fig. 2)

Author Reply: Revised to "LAT was derived by applying a latitudinally dependent correction (ΔLT; Fig. 4). ΔLT values were set to –2 °C, –3.5 °C, –7.5 °C, and –9 °C for ~0°, ~30°, ~60°, and ~80° N, respectively, following temperature differences observed in coastal cities of the eastern Atlantic (Weather Spark)." L244. ΔLT is the latitude-dependent correction applied when converting LMMT to LAT. L263.

- _Sect. 2.7.1: This section is quite hard to follow since many abbreviations are used. Maybe it would help to spell out the abbreviations from time to time.

Author Reply: Added **Table 3.** Definitions of abbreviations used in Equations 9–24 (all values represent family-level parameters). Revised to Diversity for each event and recovery interval is calculated as (Table 3): L317.

- _L. 244-248: I think it should already be mentioned here that different scenarios are analyzed.

Author Reply: Removed "Before mass extinction events, SRC events values follow gradual warming trends as described in Table 2.".

- _L. 249-252: I think it would be helpful to provide a brief description of the different events. Some description is given in Sect. 3.2, but I believe that including such a description earlier on would give the reader a better understanding.

Author Reply: Removed this description from the method section. SRC values are shown in Tables 2a-2c. Added "Future metazoan diversity changes were estimated using Table 2, as constructed from Tables 1, 4, 5 and A1–A4, which then generate Table A5 and Figure 5. The core calculations follow Equations 9 and 10, with SRC and RR values provided in Tables 2a–2c and 6." L428 in Results.

- _L. 252: What exactly is the survival area rate and what is the difference to the survival rate?

Author Reply: I use the Extinction Area Rate (EAR) instead of the survival area rate (SAR).

Added "When the global average temperature equivalent surface (GATEL) exceeds 37 °C (GATEL30)—the threshold at which low-latitude regions become uninhabitable (Fig. 2)—survival rates are further adjusted using the Extinction Area Rate (EAR [km^2/km^2]) and family-level diversity rate across each latitude (DRL)."

L303. Added "EAR Extinction Area Rate in all land and ocean (km^2/km^2)" in Table 3.

• _L. 256-257: What exactly do the rates StR, SwR, UR, and DR describe?

Author Reply: I do not use them in the present manuscript.

• _L. 259: Could you explain more clearly how the SAR is calculated?

Author Reply: Added "The Extinction Area Rate (EAR) is determined solely by the 46 °C threshold using Figure 4. When warming-driven extinction occurs within latitude bands of 0–10°, 0–20°, 0–30°, 0–40°, 0–50°, 0–60°, 0–70°, 0–80°, and 0–90°, the EAR values for species (EARS) are 0.17, 0.34, 0.50, 0.64, 0.76, 0.86, 0.94, 0.98, and 1.00, respectively, assuming equivalent contributions from land and ocean surfaces. EAR for species values are converted to EAR for family values using Figures 1b and 1c of Kaiho (2022). These EAR values are derived from GATEL, GATES, GATEU, and GATED (Section 2.4; Fig. 4; Table 4)."

L379.

Added Table 4 and the caption "The upper portion (table a) shows integrated family-level values derived from genus-level diversity (table b). Genus-level diversity per km² is based on Li et al. (2021), with conversions to family-level diversity following Kaiho (2022), Figure 1.".

• _L. 263: I cannot follow the argumentation here. Why should SARD approximate SARS?

Author Reply: This is due to effect of deep-water anoxia under high temperatures for metazoan diversity. Deep-water anoxia reduces metazoan diversity under lower temperature than surface-water temperature. I use Extinction Area Rate for deep-water metazoans (EAR_D) instead of Survival Area Rate for deep-water metazoans (SAR_D) and RRWA in the present manuscript. Added "$ERWA_D$, the extinction rate due to warming and anoxia for marine groups, is defined as**:**

GAT <36°C (events 1–4, 7): $ERWA_D = 0$

GAT ≥36°C (events 5, 6, 8–11): $ERWA_D = 0.9$ **(**anoxia-driven**)**

GAT ≥48°C (events 12–16): $ERWA_D = 1$ **(**warming-driven**)** (15) L338.

$RR_{\mathbf{M}} = RRO \times RRC \times RRWA$ (17) L349.

$RRWA_M = SR_{SM} \times 0.67 + SR_D \times 0.33$ (20)" L351 to obtain recovery rate in marine ($RR_{\mathbf{M}}$) and Recovery Rate under long-term warming and oceanic anoxia conditions in marine ($RRWA_M$).

RR_M: Marine Recovery Rate

$ERWA_D$: Extinction Rate by short-term Warming and oceanic Anoxia for deep-water metazoans

$RRWA_M$: Recovery Rate under long-term Warming and oceanic Anoxia for marine metazoans (Table 3)

Deleted "EAR_D is approximated by EAR_S. For Events 8–16 and all non-events after Event 11, EAR_D is set equal to EAR_S" and revised to "Consequently, Equation 15 is used for recovery rate (RR) for marine metazoans because GAT exceed end-Permian highest GAT 36 °C during Events 5, 6, and 8–11." In L395.

• _L. 268: How did you determine the impact of food scarcity on survival rates?

Author Reply: Revised to "Food Scarcity Rate (FS) is set as Survival Rate in Table 4 using GAT of GATEL and GATES in Figure 2, because the food resources of subterranean and deep-sea metazoans are largely derived from superterranean and surface-water biota (Tables 2a–2c)." L342.

• _L. 275: And the other events?

Author Reply: Revised completely.

• _L. 285-286: Is this reasonable? The limitations of this assumption should be discussed.

Author Reply: Revised to "Although oceanic primary producers are dominated by phytoplankton, both C_3 and C_4 photosynthetic pathways occur in marine environments (Reinfelder et al., 2000, 2004)." L398.

• _L. 287-293: I cannot follow here. Why are metazoans extinct at 0.97 Gyr if 2% remain? And don't you state in other parts of the manuscript (e.g., the Abstract, l. 460, and the Conclusions) that according to your calculations, metazoans go extinct at 0.7 and not 0.97 Gyr?

Author Reply: 0.97 Gyr represents the timing of the C_4 plant crisis, not the timing of metazoan extinction.

• _L. 304: What exactly is numerical age?

Author Reply: Revised to "T is the numerical time variable in Gyr." L365.

• _Sect. 3.1: I think this description would have been more helpful in the Methods section somewhere between Sects. 2.5 and 2.7. Then the reader could better understand the different survival rates etc.

Author Reply: Completely revised.

• _L. 364: What exactly do you mean by abrupt climate events? Are you referring to volcanic eruptions and meteorite impacts? If yes, I recommend stating this here again.

Author Reply: Revised to "Superimposed on this long-term trend are abrupt climate events associated with large igneous province volcanism and major impact events." L. 414.

• _L. 385-388: Could you also give current numbers for comparison?

Author Reply: Revised to "The survival rate (SR) and recovery rate (RR) represent changes in family-level diversity, calculated relative to modern values of 610 insect families, 315 tetrapod families, and 950 marine metazoan families." L325.

• _L. 592: Are you sure that your study is the first to reveal that?

Author Reply: Removed "is the first to".

• _Fig. 1:

o I do not understand what the green open diamond symbols denote exactly. Can you maybe explain again in other words?

Author Reply: Revised to "Green open diamonds show temperatures immediately preceding each extinction." in Figure 2 caption.

o Would it be possible to add some sort of legend to the atmospheric oxygen level graph that specifies the impact on metazoans?

Author Reply: Added "The gray gradient in panel (c) indicates the magnitude of oxygen-related constraints on metazoan diversity (see Equations 21–22 in Section 2.5), with darker shading indicating stronger limitations." in Figure 2 caption.

• Fig. 2 (l. 630): Not only silhouettes of terrestrial plants are shown, so maybe write "silhouettes of metazoans and terrestrial plants"?

Author Reply: Revised to "Silhouettes of metazoans depict approximate diversity levels and associated oxygen concentrations." in Figure 3 caption.

• Fig. 3: The yellowish-green is hard to distinguish from the green, so maybe use a different color?

Author Reply: Revised it to yellow.

• Table A2: What is SD? What does aftermath warming mean?

Author Reply: Revised SD to standard deviation. Added: SD: standard deviation. Revised Aftermath warming to Warming.

• _L. 720 and 725: before or after?

Author Reply: Revised to "Underlined and double-underlined values indicate family numbers before and after extinction events, respectively."

• _L. 727-728: Why do the underlined numbers occur just before major mass extinction events if they represent periods of recovery? Something seems wrong here.

Author Reply: Underlined numbers represent recovery periods following extinction events.

Technical corrections

• _L. 43: have ~~historically~~ triggered historical mass extinctions

Author Reply: Revised to "triggering mass extinctions throughout the past 500 Myr" L51.

• _L. 61: This manuscript was written by only one author, right? I would use "I" instead of "we"; there are other occurrences throughout the manuscript.

Author Reply: Revised to "I" for all.

• _L. 89 and 96: I think it should be "Past records of"

Done

- _L. 204: LM~~m~~MT

Done

- _L. 213: 2.5 m~~eters~~

Done

- _L. 222: GATES values are ~~common~~ equal

Done

- _L. 237: where~~,~~ D_t represents

Done

- _L. 324: 1 m~~eter~~

Done

- _L. 378: “However” does not seem to fit here.

Deleted “However”.

- _L. 398: primary productivity?

Yes, done

- _L. 430: estimating ~~of~~ the future diversity

Done

- _L. 504: illustrate~~s~~

Done

- _L. 569-573: This is a repetition of l. 566-569 and should be deleted.

Done

- _Fig. 2:

o Atmospheric oxygen level relative to for present atmospheric level

o Diversity rate relative to for the Paleozoic maximum

Done

- _L. 659 and 729: the Methods section

Done

- _L. 676: The capitalization in this sentence seems odd.

Done

- _L. 686: rates in the future

Done

- _L. 687-688: ~~for~~ compared to terrestrial plants

Done

• _Table 2: ~~in~~ at the family level

Done

• _Table A2: Earth's average surface temperature ~~of~~ including the long-term trend, long-term cy-cle, and short-term events with temperature anomal~~y~~ies and decreasing CO_2 and SO_2 emis-sions ~~decreasing rate~~ due to the decrease in mantle potential temperature during major mass extinction events from 0.7 billion years (Gyr) before the present to 1.5 Gyr into the future

Done

2. Reviewer 2

General comments

This manuscript presents a novel and comprehensive model that predicts the lifespan of metazoans on Earth over the next 1.5 billion years. It combines a wide range of geological, climate, and biological data to create a compelling narrative about the long-term future of complex life. The main conclusion—that metazoans will go extinct in approximately 700 million years, much earlier than previous estimates—is a significant and provocative contribution. However, given the immense timescale and the complexity of the integrated model, it is essential to carefully present assumptions, uncertainties, and limitations to address skeptical readers convincingly.

This is a potentially high-impact manuscript that aligns well with the scope of this journal. Its bold projections are its main strength. To maximize its impact and increase the chances of publication, the authors need to strengthen the presentation regarding the treatment of uncertainty and provide more robust justifications for the key parameters that drive the model. By doing so, they can turn a compelling thought experiment into a foundational and highly cited piece of future Earth system science. I put specific comments about each section below.

Specific comments

[introduction]

While the author currently identifies several individual gaps, such as cyclical rhythms " (L. 40), have not yet been fully incorporated, and abrupt events " (L. 46) have not yet been factored in," this can feel somewhat fragmented; they could be woven together to create a single, compelling argument for why your study is necessary. The author can reframe the problem to highlight the interaction of multitimescale forcings as the central, unexplored challenge. I recommend adding a concise, overarching problem statement just before your final thesis paragraph (L. 48). Moreover, the final paragraph should then directly answer this problem statement. The list of seven critical factors is comprehensive, but the paragraph's impact will be greater if it highlights the integrative model itself as the core novelty.

The transitions between the main ideas, such as long-term trends, cycles, and abrupt events, can be made smoother, and the link between physical forcings and biological impacts can be clarified. A key conceptual point is the difference between predictable cycles and unpredictable events. Strengthen this transition by adding a sentence that clearly contrasts their timescales. For example, at the end of the cycles paragraph: “...have not yet been fully incorporated into projections of future surface temperatures. Beyond these predictable, multi-million-year cycles, Earth's climate is also punctuated by unpredictable, abrupt events...” Then, the author briefly explains how physical drivers influence biological outcomes modeled in the system. Regarding Tectonic Cycles, the author adds a phrase on how these cycles might influence plant crises or metazoan survival (e.g., through changes in continental configuration that affect weathering rates or create or eliminate refugia). Additionally, regarding abrupt events, the author can include a sentence explaining that these events are modeled as drivers of "step-changes" in biodiversity, which can reset recovery trajectories.

The author can enhance clarity and scientific rigor by refining specific sentences. The sentence "Global warming will accelerate terrestrial weathering..." serves as a key link. The author should add a few words to clarify how the mechanism works, which would add depth. In the final paragraph, the sentence "Projections are based on temperature modeling, thermal tolerance limits..." appears to preview the Methods section. Therefore, the author can rephrase it as, “Our model projections combine future scenarios of temperature and oxygen levels with established data on metazoan thermal tolerance and diversity trends.”

The final two paragraphs contain some repetitive information and could be merged to create a more powerful and concise conclusion to the introduction. The author can integrate the description of metazoan evolution and thermal tolerance into the core thesis paragraph. This creates a single, strong paragraph that states what you did, what you based it on, and the scope of your analysis.
Author reply: In response to the comments regarding the introduction section, I revised the opening to begin with: “Metazoans first appeared and diversified around 700–500 million years ago, evolving from simple cnidarian-like organisms into more complex groups such as arthropods and vertebrates during intervals

of rising oxygen and shifts from icehouse to greenhouse climates (Erwin, 2015; Kaiho et al., 2024). After transitioning onto land approximately 400 million years ago, metazoans eventually gave rise to humans (genus *Homo*) roughly 3 million years ago. Despite this long evolutionary history, the future trajectory of metazoan diversity remains poorly understood." L22.

I then summarized previous studies projecting future life and biodiversity on Earth, explained the underlying causes and mechanisms influencing long-term biodiversity trends, and finally added the following new paragraphs to clarify how these factors are addressed in the present study.

Methods:

[Methods: 2.1]

The statement "Assuming that the icehouse-greenhouse cycle and major mass extinctions continue at the same pace as in the past" (L. 66) is a significant assumption that is central to your model. This requires a brief justification. Is there a reference supporting the consistency of these cycles over billionyear timescales? A sentence citing relevant geological timescale studies would greatly strengthen this.

Author reply: Revised to: "**4.2.2 Long-term hothouse–icehouse cycles**

Long-term (0.35–0.30 Gyr) climate cycles are reconstructed from sea-surface temperature (SST) estimates based on oxygen-isotope compositions of fossil apatite and calcite, together with evidence of glacial diamictites across multiple paleolatitudes. Over the past ~1 Gyr, three complete long-term cycles have been identified, supporting the assumption that similar cycles will continue (Fig. 5). These cycles were driven primarily by plate-tectonic and mantle processes associated with supercontinent assembly and breakup (Heron, 2018). The expected formation of the next supercontinent, Amasia, around 0.25 Gyr (Yoshida, 2016), aligns with the projected onset of the next major icehouse interval (Fig. 2).

Mantle temperatures are expected to remain sufficiently high to sustain large-scale convection—~1350 °C at present, decreasing to ~1250 °C at 0.7 Gyr and ~1200 °C at 1.0 Gyr (Mello and Friaça, 2019). However, progressive CO_2 depletion due to enhanced continental weathering (driven by rising solar luminosity) will reduce the amplitude of future cycles, diminishing their climatic influence during the intervals when terrestrial and marine metazoan extinctions ultimately occur." L550.

The method assumes that the relationships between temperature/O_2 and biodiversity observed in the deep past will also apply to the entire future of complex life. This core assumption should be clearly acknowledged as a potential limitation or justified with a solid rationale.

Author reply: Added subsection 4.2 Reliability of future biodiversity projections to discuss the reliability of future biodiversity projections depends on six key considerations:

(1) whether solar luminosity remains the dominant control on the persistence or extinction of life,

(2) whether long-term hothouse–icehouse cycles continue to operate,

(3) whether abrupt climate perturbations associated with mass-extinction-scale events continue to occur,

(4) whether CO_2 decline induces major plant crises,

(5) whether atmospheric oxygen decline significantly alters metazoan diversity, and

(6) whether life can survive the ongoing anthropogenic crisis, which includes CO_2-driven warming, pollution, deforestation, and the risk of full-scale nuclear conflict. L542.

Although the author mentions specific groups later, the term "metazoan extinction" (L. 72) in point 3 is quite broad. It would be helpful to clarify early on that your study focuses on the specific groups listed—marine metazoans, terrestrial tetrapods, and insects —as proxies for overall metazoan diversity.

Author reply: Added "insects, terrestrial tetrapods, and marine metazoans" in the final sentence in the introduction section.

The nature of these abrupt large-scale future climate events (Events 1-16; L. 81 and 83) remains unclear. Are they modeled as analogues to the Big Five? Are they stochastic events? A brief explanation of how these were defined and selected would be very helpful.

Author reply: Added "(Events 1–16, modeled as analogs to the "Big Five" mass extinctions)" L146.

The phrase "framework that includes temperature trends, oxygen levels, and C3-C4 plant crises" (L. 78-79) is too general. The author needs to describe the actual model. Is it a statistical correlation? A dynamic system model? A set of conditional rules?

Author reply: Revised to "Abrupt events (Equation 9) are treated as independent of long-term climate trends (Equation 10), as their short duration precludes substantial modulation by gradual climate evolution. Combined with physiological constraints on metazoans, these cyclic and abrupt processes are expected to operate similarly in the future. This framework also accounts for the long-term decline in mantle potential temperature (Subsection 2.3), because mantle degassing influences both climatic cyclicity and large-scale extinction events.

A further assumption is that progressive atmospheric CO_2 drawdown—accelerated by intensified continental weathering—will trigger recurrent plant crises, while a concurrent decline in atmospheric oxygen will ultimately lead to the extinction of metazoan life.

The analysis proceeded through the following steps:

A. Baseline reconstruction of historical diversity, climate, and oxygen levels (see Subsection 2.2).

B. Projection of future temperature trends (see Subsection 2.3).

C. Determination of metazoan thermal tolerance limits, where local extinction thresholds are scaled to

global mean surface temperature based on latitudinal gradients (see Subsection 2.4).
D. Development of an integrated future-diversity model, combining elements from steps A–C with long-term atmospheric CO_2 and O_2 projections, while accounting for food scarcity effects triggered by the collapse of surface-dwelling metazoans (see Subsection 2.5)." L80.

Then, C3-C4 plant crises (L. 79) are mentioned but are not introduced earlier. The author should briefly explain what this crisis involves and why it is a factor in your model.

Author reply: I explain C3–C4 plant crises in the introduction section "This warming accelerates continental weathering, which removes atmospheric CO_2 over timescales of hundreds of thousands of years, triggering cascading biological crises. Declining CO_2 will differentially affect C_3 and C_4 plants because of their distinct photosynthetic pathways: C_4 plants tolerate hotter, drier, low-CO_2 conditions better than C_3 plants. Thus, C_3 plants (including most trees) are expected to decline first, followed by C_4 plants, ultimately leading to collapse of metazoan ecosystems (Reinfelder et al., 2000, 2004; Mello and Friaça, 2019; Ozaki and Reinhard, 2021)." L40.

Regarding methodological precision, the author used "compiled records (L. 63)" and "analyzed the relationship (L. 64)," but should specify the particular statistical methods, such as correlation analysis and regression modeling.

Author reply: Revised to "To project the future lifespan of metazoans on Earth, I developed a multi-step model that integrates relationships derived from past climate patterns and biodiversity dynamics (Fig. 1)." L72. And "The analysis proceeded through the following steps:
A. Baseline reconstruction of historical diversity, climate, and oxygen levels (see Subsection 2.2).
B. Projection of future temperature trends (see Subsection 2.3).
C. Determination of metazoan thermal tolerance limits, where local extinction thresholds are scaled to global mean surface temperature based on latitudinal gradients (see Subsection 2.4).
D. Development of an integrated future-diversity model, combining elements from steps A–C with long-term atmospheric CO_2 and O_2 projections, while accounting for food scarcity effects triggered by the collapse of surface-dwelling metazoans (see Subsection 2.5)." L88.
The detailed methods are shown in Subsection 2.2. Past diversity, climate, and oxygen baselines.

At point 3 (L. 69~), the transition from "local extinction temperature" to "global average surface temperature" at which extinction occurs is a crucial scaling step. This process should be clearly explained in the detailed methods (2.6), and the summary should hint at its complexity (e.g., "...was scaled to a global average surface temperature using latitudinal gradients").

Author reply: I have revised the section as "2.4 Metazoan thermal tolerance limits" in L193 and Figure 4. Revised to "C. Determination of metazoan thermal tolerance limits, where local extinction thresholds are scaled to global mean surface temperature based on latitudinal gradients (see Subsection 2.4)."

L91.

Finally, in the last paragraph (L. 85~), the sentences about gradual extinctions (orange curve) and the estimated durations (0 Gyr and 0.05 Gyr) seem somewhat out of place in the method summary. They are better suited for the Results section or a dedicated part of the detailed methods.

Author reply: Moved to method section, L297.

The "0 Gyr" duration for temperature anomalies is confusing and needs clarification.

Author reply: Removed it.

Revised first paragraph:

To project the future lifespan of metazoans on Earth, we developed a multi-step model that integrates relationships derived from past climate and biodiversity dynamics. Our core assumption is that the pacing of icehouse-greenhouse cycles (~0.3 Gyr) and major mass extinctions (~0.094 Gyr), along with the physiological constraints on metazoans, will remain consistent in the future [references, if possible]. The analysis proceeded as follows:

1. Past Climate and Diversity Baselines: -- correspond to subsection 2.2
2. Future Temperature Projections: -- correspond to subsection 2.3
3. Metazoan Thermal Tolerance Limits: -- correspond to subsection 2.4
4. Oxygen-Biodiversity Relationship: -- corresponds to subsection 2.5
5. Integrated Future Diversity Model: -- corresponds to subsection 2.6

The paragraph about five past events, 16 events, and gradual extinctions (L. 81-88) could be moved or integrated into points 2 and 5 above for better flow.

Author reply: Revised "2.1. Method summary" using the above sentences.

To maintain consistency across subsections, the author should verify that the titles of subsections 2.2 through 2.6 directly correspond to points 1 through 5 in the Method summary and expand on them. For example, 2.2 should include a detailed methodology for point 1, "Past Records." Therefore, if possible, the author should either revise the outline based on your Method summary or revise the Method summary itself.

Author reply: Revised these subsections to fit the above *1* to *5*. Added "To estimate future metazoan diversity, I compiled past records of global surface temperatures and biodiversity. Earth's climate history has exhibited a cyclical pattern of 0.35–0.30 Gyr since -1.0 Gyr (Fig. 2). This cycle consists of extended greenhouse phases lasting around 0.2 Gyr, followed by shorter icehouse phases of approximately 0.1 Gyr (Scotese et al., 2021; Torsvik et al., 2024; Vérard, 2024). To incorporate this climate cycle, I applied an 8°C temperature anomaly between icehouse and greenhouse periods (Bond and Grasby, 2017) to Mello and

Friaça's model (Fig. 2, Table A1)." L111, and "Although climate cycles evolve over long timescales, mass extinctions unfold far more abruptly. Both processes contribute to global warming and may therefore shorten the time remaining before the eventual disappearance of metazoans in the distant future." L129 in subsection 2.2.

The subsections (2.2 to 2.6 (or 2.7)) must flesh out the details summarized in 2.1. For each step, the author needs to specify: About data sources, the author mentions specific databases or publications, and provides tables (e.g., Tables A1 and A2).

Author reply: For 2.3 Future temperature projections, for example, I revised "A coherent framework for projecting future global temperatures is illustrated in Figure 1 (highlighted in pale red, yellow, and green). Surface temperature estimates were generated using long-term warming trends, cyclical climate variations, and abrupt events (Events 1–16, modeled as analogs to the "Big Five" mass extinctions), following Equations 1–7 in this subsection. Mantle temperature is treated as a key control on abrupt events (Equations 4–7). The same pacing of icehouse–greenhouse cycles (~0.3 Gyr intervals) and major abrupt extinction events (~0.094 Gyr intervals) is applied to future climate projections. The uncertainties associated with these cyclicities provide estimates for the timing of complete metazoan extinction, with error margins of ±0.1 Gyr for climate cycles and ±0.03 Gyr (1σ) for abrupt event timing." L143. Done for the other subsections and data sources.

About analytical techniques, how did the author analyze the relationship? Was it a linear regression? A non-linear model? Specify the statistical tests and the software/tools used.

Author reply: Added "All datasets were generated using the equations and baseline data outlined in Subsections 2.2–2.5. All calculations were executed in Microsoft Excel, and the resulting data are presented in the accompanying tables." In L108 subsection 2.1.

About Quantitative Definitions, what are the numerical thresholds for "low, mid, and high latitudes"?

Author reply: "------ in low–mid latitudes (0°–60°) and decline to 35–40 °C in high latitudes (60°–90°)" L213 and "low-latitude (0–30°)" L303.

What defines a "C_3-C_4 plant crisis" in your model? Define these operationally.

Author reply: Revised to "The C_3 plant crisis is defined at ~0.15 mbar CO_2, and the C_4 plant crisis at ~0.01 mbar CO_2 (Fig. 2)." L313.

Model Parameters: The values "0.3 Gyr" and "0.094 Gyr" are key model inputs. Justify these choices with references beyond the general (Erwin et al., 1987). How sensitive are your results to these specific values?

Author reply: Revised to "In contrast, major abrupt climatic perturbations capable of triggering mass extinctions are assumed to continue recurring at ~0.094 Gyr intervals, based on the mean recurrence time calculated from age data in Kaiho (2025). Importantly, the specific values chosen for these intervals do not influence the 0.1 Gyr–resolution results presented in the abstract (Fig. 2)"L76.

[Methods: 2.2]

The issue with this section is the jump from describing the data to stating the objective. The sentence "To estimate future abrupt climate changes and biotic crises, we selected the five largest mass extinctions..." (L. 91-92) is an objective, not a method. Thus, the author should restructure the text to first present the data and then explain the analytical step.

Author reply: This section has been revised as shown above.

The author also needs to provide a more detailed explanation of how they selected and used these "five major mass extinctions." This clarifies the reason for choosing specific events and helps ensure the methodology can be reproduced.

Author reply: Revised to "I selected the five major mass extinctions, each marked by abrupt environmental disruption and >35% marine genera loss—equivalent to >60% species extinction—based on Bambach (2006) and Kaiho (2022). Family-level extinction percentages capture severe biodiversity losses across taxa. Marine metazoan family-level extinctions were ~22% (end-Ordovician), 21% (Late Devonian), 50% (end-Permian), 20% (end-Triassic), and 15% (end-Cretaceous) (Sepkoski, 1982). Terrestrial tetrapod extinctions were 54%, 21%, and 38% at the end-Permian, end-Triassic, and end-Cretaceous, respectively (Table A2; Benton, 2010). Insects experienced 35%, 14%, and 8% extinction across the same events (Table A3; Labandeira & Sepkoski, 1993). Because terrestrial tetrapods and insects originated shortly before the second mass extinction, diversity data are unavailable for the first two events; therefore, average extinction percentages from the five marine and three terrestrial crises were used.". L116.

The author mentions two different types of data: 1) long-term climate cycles (icehouse-greenhouse) and 2) short-term temperature anomalies during extinction events, but the connection between them is not explained. Please briefly explain the role of each dataset in your overall model.

Author reply: Added "Abrupt events (Equation 9) are treated as independent of long-term climate trends (Equation 10), as their short duration precludes substantial modulation by gradual climate evolution. Combined with physiological constraints on metazoans, these cyclic and abrupt processes are expected to operate similarly in the future. This framework also accounts for the long-term decline in mantle potential temperature (Subsection 2.3), because mantle degassing influences both climatic cyclicity and large-scale extinction events." L79 in subsection 2.1.

The final sentence (L. 95), "These data are applied in section 2.2," is redundant as it is already within section 2.2.

Author reply: Removed this sentence.

[Methods: 2.3]

The paragraph (L. 97-L. 104) states that “marine metazoan diversity rates” were “derived from past records,” but it does not provide a source for these diversity rates, only for the oxygen levels. This creates a notable gap in reproducibility. The author must provide the reference(s) for your biodiversity data.

Author reply: Family-level extinction percentages capture severe biodiversity losses across taxa. Marine metazoan family-level extinctions were ~22% (end-Ordovician), 21% (Late Devonian), 50% (end-Permian), 20% (end-Triassic), and 15% (end-Cretaceous) (Sepkoski, 1982). L117

What does a "diversity rate" of 0.04 or 1.0 actually mean? Is it a count of families or genera normalized to a maximum value? Is it an estimated measure of richness? Without a clear operational definition, the metric remains ambiguous. Please provide a brief explanation of how the calculation is performed.

Author reply: Revised to “The survival rate (SR) and recovery rate (RR) represent changes in family-level diversity, calculated relative to modern values of 610 insect families, 315 tetrapod families, and 950 marine metazoan families.” L325.

The second paragraph (L. 105-108) is mostly interpretative. Phrases such as “suggests that there is a positive relationship,” “significant declines,” and “appear to require higher oxygen levels” are conclusions based on the data. Remove the entire second paragraph from the Methods section. These should be moved to your Results section (to show the relationship) and the Discussion section (to discuss the possible reasons).

Author reply: Description on oxygen in this subsection has been incorporated into Section 2.5. Moved the interpretation to the discussion section.

The final sentence (L.108), “These interpretations are further applied in Section 2.4,” should be rephrased to emphasize the data and relationship, not the interpretation. The author should rephrase it to something like, “The quantitative relationship between O2 and biodiversity established here (Figure 3) is used in Section 2.4 to describe the specific action, such as constraining future diversity projections based on predicted oxygen levels.”

Author reply: Removed this sentence.

[Methods: 2.4]

Averaging percentages from different extinction events, which had vastly different causes and selective pressures, into a single "future diversity loss" value is a highly simplified modeling choice. The author should justify why this is a valid approach for long-term projection. Please add a sentence or two explaining the rationale. The author should also acknowledge the limitations of this approach.

Author reply: Added "The uncertainties associated with these cyclicities provide estimates for the timing of complete metazoan extinction, with error margins of ±0.1 Gyr for climate cycles and ±0.03 Gyr (1σ) for abrupt event timing." L149. "Importantly, mass extinctions are caused not only by global warming but also by reductions in sunlight due to stratospheric aerosols, which induce global cooling, along with decreases in precipitation. Accordingly, the total extinction rate for each metazoan group is treated as the sum of the past major mass-extinction rate and the additional extinction rate attributable specifically to global warming during future intervals in which excess LDMT conditions exceed 46 °C." L328. "Abrupt climate changes linked to mass extinction events are inferred from oxygen-isotope records of apatite and calcite associated with the five major mass extinctions. Mantle-temperature projections indicate that plume-related large igneous province volcanism will remain possible, and asteroid impacts are expected to continue occurring at rates inferred from lunar and terrestrial cratering histories (Neukum, 1983; Glikson, 1999; Hartmann et al., 2007; Kaiho & Oshima, 2025). Such high-magnitude, short-duration events will therefore likely persist as sources of abrupt climatic disruption superimposed on long-term warming.

Short-term SO_2, soot, and CO_2 releases exert minimal influence on multimillion-year temperature trends because their climatic impacts typically last <0.1–1.0 Myr. Over geological timescales, natural recovery processes—such as sulfur deposition and CO_2 drawdown—dampen these perturbations. As a result, long-term warming, cyclical climate fluctuations, and abrupt catastrophic events (as represented in Equation 1) collectively define the global temperature trajectory (Fig. 2)." L568.

The author lists five events for marine metazoans but only three for tetrapods and insects. Why is there a discrepancy? Is the author averaging five events for the marine group and three for the terrestrial group? This needs to be clarified.

Author reply: Added "Because terrestrial tetrapods and insects originated shortly before the second mass extinction, diversity data are unavailable for the first two events; therefore, average extinction percentages from the five marine and three terrestrial crises were used." L122."

The subsection is titled "Past and future extinction percentages and the interval," but the content does not mention any time interval. The 0.094 Gyr extinction cycle from your initial summary is a crucial parameter. This is where to define it. The author includes the methodology for the interval here.

Author reply: In contrast, major abrupt climatic perturbations capable of triggering mass extinctions are assumed to continue recurring at ~0.094 Gyr intervals, based on the mean recurrence time calculated from age data in Kaiho (2025). L76.

[Methods: 2.5]

The first paragraph (L. 120-123) doesn't serve well as an introduction to this section because the framework for temperature estimation is unclear. Additionally, the section reads more like a collection of individual sub-models rather than a coherent methodology.

Author reply: Added "A coherent framework for projecting future global temperatures is illustrated in Figure 1 (highlighted in pale red, yellow, and green). Surface temperature estimates were generated using long-term warming trends, cyclical climate variations, and abrupt events (Events 1–16, modeled as analogs to the "Big Five" mass extinctions), following Equations 1–7 in this subsection. Mantle temperature is treated as a key control on abrupt events (Equations 4–7)." L144.

The most significant gap is clarifying how the mass extinction events are timed and situated within the 2.5 Gyr timeline. Are they periodic, random, or triggered by a specific threshold? This is a key factor affecting the results and remains undefined.

Author reply: Added "The same pacing of icehouse–greenhouse cycles (~0.3 Gyr intervals) and major abrupt extinction events (~0.094 Gyr intervals) is applied to future climate projections. The uncertainties associated with these cyclicities provide estimates for the timing of complete metazoan extinction, with error margins of ±0.1 Gyr for climate cycles and ±0.03 Gyr (1σ) for abrupt event timing." L147.

Several critical numbers and equations in this Section are presented without explanation, making it impossible for a reader to evaluate or reproduce your work:

1) Why is there an 8 °C temperature difference between the icehouse and greenhouse periods? (L. 129) Bond and Grasby (2017) are probably insufficient because their study focuses on specific events. Using a single value over 2.5 Gyr is a big oversimplification that needs strong justification. Therefore, the author should provide a brief context.

Author reply: Revised to "To incorporate this cyclicity, I applied an 8 °C temperature anomaly between icehouse and greenhouse states (Scotese et al., 2021) to the Mello and Friaça model (Fig. 2, Table A1)." L113. "ΔTc is 8 °C maximum gradually decreasing to 0 °C at 1.2 Gyr lasting till >1.5 Gyr during greenhouse periods and 0 °C during icehouse phases. 8 °C is anomaly between icehouse and greenhouse intervals based on Phanerozoic temperature reconstructions by Scotese et al. (2021). The gradual decrease is due to a gradual CO_2 decrease by enhanced continental weathering caused by a gradual solar luminosity increase. Earth's climate history has exhibited a cyclical pattern of 0.35–0.30 Gyr since -1.0 Gyr (Fig. 2). This cycle consists of extended greenhouse phases lasting around 0.2 Gyr, followed by shorter icehouse phases of approximately 0.1 Gyr (Scotese et al., 2021; Torsvik et al., 2024; Vérard, 2024). ΔTc values are adjusted based on the well-known climate model result that a doubling of CO_2 produces a 1.5–4 °C (>66% certainty) and 3 °C (best estimation value) increase in surface temperature (Sherwood et al., 2020; Table A1). Starting from the current global average surface temperature of 14 °C (icehouse state), future temperature variations were projected (Table A1; orange curve in Fig. 2). Because the 0.35–0.30 Gyr climatic periodicity may vary in the future due to mantle cooling and increased solar luminosity, these variations could introduce a maximum uncertainty of 0.1 Gyr in the timing of each metazoan diversity phase. This uncertainty was used to constrain the onset of both the diversity decline and final extinction phases. The 0.1 Gyr discrepancy reflects the relatively short duration of individual icehouse periods. However, this effect is expected to be minor owing to the progressive decline in CO_2 levels and the diminished temperature anomalies during the metazoan crisis interval." L161.

2) These equations (L.156-161) are the core of your event-based temperature calculation, but they are presented as a "black box." Where do the constants, such as -8.9, 9.9, 2/3, 9.9, 0.00108 …, originate from? The author cites Kaiho et al. (2022), but it is unclear whether these are empirically derived relationships from that paper or if the author has manipulated their data. This is the most critical part of the section to expand on.

Author reply: Added "Where T_m is mantle temperature, E is activation energy (74 kcal/mol for CO_2 release and 67 kcal/mol for SO_2), t_s and t_i are heating durations, and 1423–1603 K represent typical sill and mantle temperatures. The modern mantle temperature is 1603 K (Mello and Friaça, 2019), and the average initial sill temperature is 1423 K (Aarnes et al., 2010); the 180 K difference reflects typical cooling during sill formation. Equations (4) and (5) represent best-fit curves derived from the heating experiments of Kaiho et al. (2022) and Kaiho (2024)." L205.

3) "A 50% reduction in CO_2 and a 67% reduction in SO_2 emissions" (L. 167) are striking figures. How were they calculated? Are these the results of your model or the inputs into the model?

Author reply: Removed this sentence. These data and methods are shown in Table A2. Earth's average surface temperature including the long-term trend, long-term cycle, and short-term event with temperature anomalies and decreasing CO_2 and SO_2 emissions due to the decrease in mantle potential temperature during major mass extinction event from 0.7 billion years (Gyr) before the present to 1.5 Gyr into the future. Temperature data in Figure 2 are sourced from this Table. Gyr: giga (billion) years. temp.: temperature. The calculation methods are shown in Equations 1–7, Section 2.3.

4) The author mentions the basis for applying "the 0.3 Gyr climate cycle to the next billion years" (L.126-127), but further explanation is needed. What is the physical mechanism? Additionally, why do its period and amplitude remain constant over billions of years, despite geological changes such

as increased solar activity and/or mantle cooling?

Author reply: See the paragraph starting from L149. I use a decreasing-amplitude model in the new version, reflecting the reduction in CO_2 over time.

5) The decision to model the impact of declining mantle temperatures only for the next 1.5 Gyr (L. 168) seems arbitrary. Why not consider the entire 2.5 Gyr?

Author reply: The 2.5 Gyr timeline includes 1.0 Gyr of past data and 1.5 Gyr representing the future period analyzed.

6) The term "sill" (Ts, Ti) is used without being defined for a non-geology specialist. A brief explanation is necessary.

Author reply: Revised to "and initial sill (a tabular sheet intrusion from magma) temperature:" L203.

7) The formulation of Equation (10), Er = SD + Er(ΔTc), is problematic. It defines the total error, Er, in terms of itself, creating circular logic. Furthermore, it adds a standard deviation (SD), a statistical measure of dispersion, to an error term, Er(ΔTc), which likely represents a potential range. The description implies these components are being combined, but the equation's additive form is not logically justified. Clarification is required on the functional form of Er(ΔTc)—is it a root-sum-square, a linear addition, or another method?

Author reply: Removed this subsection. Error bars of red and blue dots in Figure 2 are only standard deviation.

8) Finally, the claim that the error is "within 0.1 Gyr" is ambiguous; it needs clarification on whether this refers to an uncertainty in age or temperature.

Author reply: Added "The 0.1 Gyr discrepancy reflects the relatively short duration of individual icehouse periods. However, this effect is expected to be minor owing to the progressive decline in CO_2 levels and the diminished temperature anomalies during the metazoan crisis interval." L173.

9) Concerning Equation 8, the derivation from the Arrhenius equation should be briefly explained or referenced.

Author reply: Added "(74 kcal/mol for CO_2 release [Jackson et al., 1995] and 67 kcal/mol for SO_2 [Concer et al., 2017])" and "Equations 6 is from the Arrhenius equation on page 174 of PAC (1996)." L209.

[Methods: 2.6]

The section outlines a logical and organized approach to determining critical thermal thresholds for metazoans, which is a key and valuable contribution. The method of converting physiological limits into the global average surface temperature required for extinction (GATE) is ambitious and clearly segmented by habitat. However, the description currently needs significant clarification and justification to meet the standards of reproducibility:

Regarding the 5 °C adjustment from the Local Monthly Maximum Temperature (LMMT) to the Local Daily Maximum Temperature (LDMT) in Section 2.6.1, point 3, why 5 °C? Is this a global average? Is it based on the Weather Spark data cited? This needs a clear justification.

Author reply: Revised to "3. Conversion from LDMT to Local Monthly Maximum Temperature (LMMT) A –3 °C correction was applied to convert LDMT to LMMT. This offset reflects the typical difference between monthly mean and daily maximum temperatures during the warmest month, based on observations from coastal cities including Singapore (~0° N), Shanghai (~30° N), Helsinki (~60° N), and Longyearbyen (~80° N) (Weather Spark)." L238. Revised 5 °C to 3 °C in related figures and tables.

Regarding the 1 °C and 5 °C Local Annual Temperature (LAT) adjustments in Section 2.6.1, point 4, the cited reference (Upchurch et al., 1998) is somewhat outdated. Is this still the most relevant source? Please briefly explain the climatic reasons behind this latitudinal gradient in temperature differences.

Author reply: Added "4. Conversion from LMMT to Local Annual Temperature (LAT) LAT was derived by applying a latitudinally dependent correction (ΔLT; Fig. 4). ΔLT values were set to –2 °C, –3.5 °C, –7.5 °C, and –9 °C for ~0°, ~30°, ~60°, and ~80° N, respectively, following temperature differences observed in coastal cities of the eastern Atlantic (Weather Spark)." L242. Added "5. Establishing warm-Earth latitudinal temperature gradients The warm-Earth latitudinal gradient of LAT was set to be 20 °C and 14 °C larger than the corresponding sea-surface temperature (SST) gradients of 17 °C and 11 °C from 0° to 90° latitude when GAT is 30 °C and 40 °C, respectively (thin oblique lines in Fig. 4a; Gaskella et al., 2022). These gradients reflect changes in solar incidence associated with Earth's axial tilt." L247.

The selection of 37° latitude for determining GATE in Section 2.6.1, point 5, appears arbitrary as stated. Why 37 °? Is this based on a global average temperature weighting? This step is crucial in determining your final GATE value and must be clearly explained. Author reply: Added "6. Determine GATE from LAT at a representative latitude LAT at 37° absolute latitude was used as a proxy for Global Annual Temperature (GAT), because modern GAT (14 °C) closely matches LAT at 37° N in oceanic climate regions (Iwaki and San Francisco; Weather Spark)." L253.

Calculate extinction thresholds (GATE values)"

The assumed future burrowing depth of 2.5 meters in Section 2.6.2 is a significant biological assumption. Why choose 2.5 m instead of 1 m or 5 m? Is there evidence that metazoans can or will burrow to this depth for thermoregulation? This requires ecological justification.

Author reply: Revised to "The extinction thresholds for subterranean metazoans (GATEU) were determined using Figure 4b. Although most modern subterranean organisms inhabit shallow depths (~10 cm), future subterranean metazoans capable of tolerating elevated surface temperatures are expected to retreat to depths of approximately 2.5 m. At this depth, the temperature difference between the Local Monthly Maximum Temperature (LMMT) and the Local Annual Temperature (LAT) is about 2 °C—low enough to allow survival. In contrast, at a depth of 1 m this difference approaches ~8 °C, which is too large for survival (Singh and Sharma, 2017). At depths ≥4 m, soil temperature becomes nearly constant throughout the year. the difference between LDMT and LMMT is less than 1 °C (Singh and Sharma, 2017). In Figure 4b, oblique LAT lines were therefore plotted 2 °C below the closed 46 °C points, representing lethal thermal limits, for subterranean animals living at a depth of 2.5 m. The warm-Earth latitudinal gradient of LAT was set to be sea-surface temperature (SST) gradients of 11 °C and 5 °C from 0° to 90° latitude when GAT is 40 °C and 50 °C, respectively (thin oblique lines in Fig. 4c; Gaskella et al., 2022)." L265.

The step-by-step process in Section 2.6.1 can be confusing because it mixes the description of what is shown in the figure with the actual methodological steps. It would be clearer to organize it as a standalone explanation. If possible, the author should rewrite 2.6.1 as a numbered or bulleted list that is independent of the figure: 1) Define the upper thermal tolerance (46ÅãC) as the average maximum daily temperature (...) at key latitudes (0°, 30°, 60°, 90°). 2) Establish the warm Earth latitudinal temperature gradient (15 °C from 0° to 90°). 3) Adjust this gradient for LMMT by applying a -5 °C correction. 4) Adjust LMMT to LAT using a latitudinally variable correction (ΔLT). 5) Calculate the GATE from the LAT at a representative latitude (3°N/S). Author reply: Added L218-248.

The text in Section 2.6.1, point 5 states, "The GATE values for St and Sw metazoans are the same as described in Section 2.3.3." However, since your structure indicates that 2.3 is about oxygen levels, this likely refers to a different part of your manuscript, which could cause confusion. All necessary information for understanding the calculation should be in this section or clearly cross-referenced.

Author reply: Revised to 7. Calculate extinction thresholds (GATE values) GATEL (land), GATES (surface water), GATEU (underground), and GATED (deep water) were derived from LAT at 37°, as shown by open dots in Figure 4. L244.

The frequent and inconsistent use of acronyms makes the text very difficult to understand. Readers must constantly refer back to remember what they stand for. Therefore, if possible, please consider adding a table: a summary that lists each metazoan group, its defined upper thermal limit, all applied corrections, and the final derived GATE value would greatly enhance clarity and reproducibility.
Author reply: Added Table 3.

[Methods: 2.7]

The three main equations of the core model are shown, but their logic and connections are not clearly explained. Equation (13) presents a problem in this recovery model. Dt-2 refers to diversity two time steps earlier, implying that recovery aims to reach a diversity level similar to what was before the last extinction event, which may not be ecologically realistic. A more common approach would be to target a recovery toward a carrying capacity or a pre-event level. The reasoning behind this needs further clarification. Equation (14) appears to apply to gradual diversity loss preceding an event. It's unclear why this is a separate equation from equation (12) and how the "Survival Rate for gradual changes" (SR) differs from SRC in practice. The model's flow between these equations is not described.

Author reply: Revised to two equations:

$D_{nE} = D_{(n-1)A} \times SRC_n \times FS_n$ [for events] (9)

$D_{nR} = D_{(n-1)A} \times RR$ [for recovery periods] (10)

Explanation of those abbreviations are in Table 3. Abrupt events (Equation 9) are treated as independent of long-term climate trends (Equation 10), as their short duration precludes substantial modulation by gradual climate evolution. (L80)

This is a critical issue that significantly hampers readability. The text uses over 20 different acronyms (SRC, SRO, RR, SR, SAR, SARS, SARU, SARD, SRCT, SRCM, StR, SwR, UR, DR, FS, GATE, etc.). Many are non-intuitive, and some are confusingly similar (e.g., SR vs. SRC vs. SRO; SARS as "Survival Area Rate" is an unfortunate choice). The author should create a nomenclature table before Section 2.7, including a list of all acronyms, their full names, and brief definitions. Otherwise, please avoid creating an acronym for every term. Use them sparingly for the most frequently used concepts.

Author reply: Added Table 3.

Many of the numerical values used in the model seem arbitrary or lack a clear, reproducible source. This presents the biggest risk to the model's credibility.

Regarding SRC for Event 0 (Anthropocene), the values of 0.95, 0.70, and 0.90 for a "full-scale nuclear war" are very precise. What is the basis for these exact numbers? The citation (Kaiho, 2023) must specifically provide these values or the model that produced them.

Author reply: Revised to "SR values for Event 0 are set at 0.95, 0.80, and 0.90, respectively, using Figure 1 of Kaiho (2022) (Kaiho, 2025b)." L326. Revised 0.70 to 0.80. 0.95 is from comparison of the insect extinction rate and that of tetrapods.

Regarding Food Scarcity (FS), a reduction of "0.1–0.5" is a very broad range. How is a specific value selected for a particular calculation? This requires a clear rationale.

Author reply: Revised to "Food Scarcity Rate (FS) is set as Survival Rate in Table 4 using GAT of GATEL and GATES in Figure 2, because the food resources of subterranean and deep-sea metazoans are largely derived from superterranean and surface-water biota (Tables 2a–2c)." L343.

Concerning "Underground Rate (UR=0.05) and Deep-water Rate (DR=0.33)," the logic for converting modern lineage proportions (e.g., 15 out of 315 mammalian families) into a future survival rate is not clearly explained. This is a major assumption that requires a strong ecological justification.

Author reply: Added "The diversities of superterranean and subterranean metazoans change independently due to GAT, whereas the diversities of surface-water and deep-water environments change independently due to both high GAT and low dissolved oxygen, as shown in Equations 11–13 (Fig. 2).". L389.

For "Recovery Rates (RR)," many RR values (e.g., 0.01-0.3 for events 8-10) are given without a clear, quantitative link to environmental conditions. The justification is qualitative ("reduced capacity," "adaptation challenges"), but the output is a precise number. There needs to be a transparent method for converting the severity of an event into a recovery rate.

Author reply: Recovery Rates (RR) are composed of RRO, RRC, and RRW. Defined these values as the following equations.

Recovery Rates in Conservative Model (Table 2a; Recovery Rates in New Evolutional Model and Continuous Worst Anthropocene Model are shown in Tables 2b and 2c, respectively):

$$RR_T = RRO \times RRC \times RRW \quad (16)$$

$$RR_{\mathbf{M}} = RRO \times RRC \times RRWA \quad (17)$$

$$RRW_T = SR_S \times 0.95 + SR_U \times 0.05 \quad (18)$$

$$RRWA_M = SR_S \times 0.67 + SR_D \times 0.33 \quad (19)$$

Survival Rates (SR) are obtained from Figure 2 and Table 4.

Oxygen-Based Recovery Rate (RRO)

Terrestrial metazoans:

During the next 0.5 Gyr: RRO = 1.0

During the next 0.5–1.05 Gyr: RRO = (1.05 – T) × 1.6

During the next >1.05 Gyr: RRO = 0.0 (20)

Marine metazoans:

During the next <0.5 Gyr: RRO = 1.0

During the next 0.5–1.0 Gyr: RRO = 1.4 –T

During the next 1.0–1.1 Gyr: RRO = (1.1 – T) × 4

During the next >1.1 Gyr: RRO = 0.0 (21)

The thresholds reflect oxygen requirements: >10% PAL for terrestrial animals (Krause et al., 2022) and >1% PAL for marine animals (Sperling et al., 2013; Lyons et al., 2014). Time intervals on RRO are based on average ages shown in Figure 2c (Ozaki and Reinhard, 2021). T is the numerical time variable in Gyr.

CO_2-Based Recovery Rate (RRC)

During the next ≤ 0.4 Gyr: RRC = 1.0

During the next 0.4–1.0 Gyr: RRC = 1.4 – T [Max], (1.0 – T) × 10/6 [Min]

During the next 1.0–1.3 Gyr: RRC = 1.4 – T [Max], 0 [Min]

During the next >1.3 Gyr: RRC = 0 (22)

Diversity loss due to CO_2 decline is assumed to proceed linearly from RRC = 1.0 to 0.0 between 0.4 and 1.3 Gyr. All rates are at the family level.

Regarding the "C_4 Plant Crisis" (L. 287), the timeline is set to "coincide approximately with event 11," and the extinction of metazoans is then "set at 0.97 Gyr." This appears to be a circular argument where the model is adjusted to fit a pre-selected outcome rather than the outcome emerging naturally from the model's mechanics. Is it true?

Author reply: In this version, I use a gradual change of RRC, resulting in "Diversity loss due to CO_2 decline is assumed to proceed linearly from RRC = 1.0 to 0.0 between 0.4 and 1.3 Gyr." Therefore, I removed this sentence.

The Methods section should describe how you calculated diversity, not what the results are. This section often overlaps with presenting results and speculative explanations, such as … expected to decline (L. 276), … are expected to evolve (L. 280), and … are expected to include (L. 290). The author should rephrase these statements to describe the model's rules.

Author reply: Done.

[Results: 3.1]

The most significant issue is the lack of a methodological link between your methods and your primary result. The "Results" section should present findings derived from the previously described methodology; however, the description of the temperature curve reads more like an input scenario than a calculated outcome. The core problem is that the reader is told what the temperature curve is, but not how it was generated. While Section 2.6 details a model for calculating extinction thresholds, it does not explain the foundational climate model that produced the temperature projection itself. The author must explicitly state the model or data source used to generate the orange curve in Figure 1. Is it an output from a climate model run under specific CO2 scenarios? An extrapolation from past climate data? Or is it derived from astronomical solutions, such as Milankovitch cycles? Crucially, you must identify the primary forcing driver (e.g., increasing solar luminosity, greenhouse gas concentrations) to provide the necessary context.

Author reply: The orange curve is an extrapolation from past climate data.

The same time periods and temperature ranges are described multiple times in slightly different ways (e.g., 0.65-0.95 Gyr vs. 0.7-1.0 Gyr). This repetition is redundant and causes confusion. Paragraph 2 (L. 352-355) describes the trend with specific future time points (0.35, 0.65, 0.95 Gyr), while Paragraph 4 (L. 359-363) restates the trend by re-binning the timeline into Phases A-E. Therefore, the author should combine these into a single, clear description, using the climate phases as the main structural framework and avoiding disconnected time points.

Author reply: Revised to "The temperature modeling methods outlined in Section 2.3 and Equations 1–8 yield the projections shown in Figure 2, indicating a long-term warming trend punctuated by abrupt climate events.

During the Phanerozoic (−0.54 Gyr to present), global average surface temperatures oscillated between ~15°C and 25°C, a range expected to persist until ~0.35 Gyr (Climate Phase A), aside from short-lived perturbations linked to major extinction events. Beyond this interval, temperatures are projected to rise progressively: to 25–30°C by ~0.7 Gyr (Climate Phase B), 30–40°C between ~0.7 and 1.0 Gyr (Climate Phase C), 40–50°C between ~1.0 and 1.3 Gyr (Climate Phase D), and eventually to ~70°C by ~1.5 Gyr (Climate Phase E; orange curve in Fig. 2)." L409.

The nature of the abrupt climate changes described in Events 5, 8, 11, and 14 in paragraph 3 (L. 356-358) remains unclear. What physical process causes these "temperature surges" of more than 10ÅãC in"<0.1 million years"? Are they inputs to the model (prescribed forcing) or results (emergent behavior)? The text currently treats them are given. We need to determine whether these are hypothetical events, representations of volcanic or tectonic activity, or outcomes from climate tipping points.

The use of "expected" and "projected" is inconsistent. Since this is a model result, "projected" is more appropriate.

The final paragraph states that Phases B-E are "triggered by" abrupt events (L. 364). This creates a causality dilemma. Is the long-term trend the primary driver, or are the abrupt events the triggers for new phases? The current description makes it seem like both, which is confusing. The author must clarify the relationship between the gradual trend and the abrupt events.

Author reply: Revised to "Among the modeled abrupt events, Events 2, 5, and 8 produce the fastest warming (<0.1 Myr), corresponding to rapid transitions from icehouse to greenhouse states (Fig. 2). Event 8 reaches temperatures sufficient to eliminate low-latitude metazoans; Event 9 extends this to low- and mid-latitude taxa; and Event 10 reaches lethal conditions for surface-dwelling metazoans globally (Fig. 2)." L423. Revised "expected" to "projected".

[Results: 3.2]

The first paragraph states diversity is "estimated using" (L. 368) several factors but provides no explanation of how this estimation is performed. What is the model? Is it a statistical correlation, a dynamic ecosystem model, or a set of threshold rules? What are the "survival thresholds" (mentioned in 3.2.1) and how are they determined? The reader cannot assess the results without understanding the fundamental rules of the model.

Author reply: Revised to "Future metazoan diversity changes were estimated using Table 2, as constructed from Tables 1, 4–7 and A1–A4, which then generate Table A5 and Figure 5. The core calculations follow Equations 9 and 10, with SRC and RR values provided in Tables 6 and 7.

Based on these results, the interval from –1.0 to +1.5 Gyr is divided into five evolutionary phases:
(1) Ancestor Phase (early Climate Phase A),
(2) Evolution with mass extinctions (late Phase A),
(3) Decline with mass extinctions (Phases B–C),
(4) Demise by mass extinctions (Phase D), and
(5) Aftermath (Phase E) (Fig. 5)." The methods are explained in the revised method subsection 2.5.

Several claims are presented as facts without justification, moving from scientific projection to pure speculation. "Large volcanic eruptions and asteroid impacts are expected to trigger…" (L. 382-383) The timing and occurrence of these specific events cannot be projected. This must be framed as a scenario or sensitivity test like "In scenarios where large volcanic eruptions occur...".

Author reply: Revised to "Large volcanic eruptions or asteroid impacts generate severe cooling followed by abrupt warming, similar to past mass extinctions. Metazoan evolutionary phases correspond to intersections between maximum global temperatures (red dots, Fig. 2) and GAT corresponding to the thermal survival limit of 46°C (Local Daily Maximum Temperature [LDMT]), above which protein denaturation occurs." L447.

The line between results and interpretation is often unclear. A Results section should present the data or model outputs), while the Discussion should explain what they mean. In this section, phrases like "This high-temperature environment will also impact..." or "will drive the complete collapse..." are interpretive. The text often states what will happen as if it is certain, based on the model, rather than just presenting the model's output. Therefore, the author should reframe to simply present the model's findings.

Author reply: Revised based on the comments.

The author provides us with specific numbers (e.g., insect families dropping from 610 to 74–103), but does not inform us how these numbers were generated. This breaks the chain of reproducibility. Therefore, when presenting a key result, briefly link it back to the methodological framework.

Author reply: Added (Fig. 5; Table A5), (Table 8), (Fig. 5), (Fig. 2), and (Table A5).

The text in this section mentions ranges (e.g., 74–103 insect families) and different scenarios (Figs. 5 and 6), but it doesn't explain the causes of these ranges. For a projection of this magnitude, a thorough exploration of uncertainty is crucial. The author needs to state which parameters are responsible for the ranges explicitly.

Author reply: Based on the new methods, no ranges are shown in the current version. However, the ranges correspond to the variation between the Conservative Model and the New Evolutional Model (Fig. A5). The reason for this difference is whether evolutionary adaptation to extremely low CO_2 and O_2 levels occurs or not.

Given the highly speculative nature of billion-year projections, using definitive language like "will," "are expected to," or "lead to" is too strong for a Results section. The author should adopt more tentative and precise phrasing that reflects the model-dependent nature of the findings. For example, the author can use phrases such as: “The model projects...”, “Under the defined scenarios...”, “Simulation results indicate...”, and “Our findings suggest...”.

Author reply: Done.

The “Aftermath” section (L. 415-428) extends beyond metazoan diversity to explore the fate of all life and the planet. While a compelling conclusion, it exceeds the stated scope of "metazoan diversity change." The author should consider whether some of this material, especially the comparison to Venus, might be better suited for the Discussion.

Author reply: Removed the sentences.

[Discussion: 4.]

This section currently reads more like a summary and extension of the results than a critical discussion. To meet the journal's standards, the work needs to be more thoroughly addressed, including the limitations, uncertainties, and broader implications, shifting from "what we found" to "what it means and how reliable it is."

Author reply: The new discussion section is composed of 4.1 Characteristics of future diversity estimation in this study, 4.2 Reliability of future biodiversity projections, and 4.3 Incomplete recoveries in metazoan diversity.

Section 4.1 (L. 430-460) mainly defends the assumptions rather than thoroughly examining their uncertainties. A robust discussion must openly acknowledge and analyze the weaknesses. Some specific gaps include:

1) The model incorporates highly uncertain components (billion-year climate, biodiversity, oxygen, plant evolution). The combined effect of these uncertainties is not addressed. How reliable is the 0.7 Gyr extinction date, considering this?

Author reply: Added a new model, New Evolutional Model — incorporates potential evolutionary adaptation to extremely low CO_2 and O_2 levels (see Tables 2b, A5 and Fig. 5).

2) The model assumes fixed thermal tolerances. The discussion should explicitly consider the possibility of evolutionary adaptation over millions of years, even if the conclusion suggests it might be limited due to fundamental physiological reasons.

Author reply: This case is Case 2 in Table 8 (see below table).

3) The survival and recovery rates are key but poorly constrained. A discussion on how sensitive the main conclusion (extinction at ~0.7 Gyr) is to these parameters is essential. Is the outcome unavoidable across a wide range of plausible values? The author can integrate a dedicated subsection, like "4.5 Model Limitations and Uncertainties," that systematically addresses these points. This demonstrates scholarly rigor and strengthens the paper.

Author reply: Added "In addition to the standard simulations, supplementary test cases were conducted in which one causal parameter from steps A–D was held constant at its initial value throughout the entire 1.5 Gyr simulation period under the Conservative Model (see Tables A6a–A6c). These auxiliary simulations are not intended as realistic projections, but rather serve to elucidate the individual contributions of each parameter to the timing of metazoan extinction relative to the baseline models." L104. The results are shown in a new section 3.3 Contribution factors in L470 and Table 7. In Conclusion: Consequently, all terrestrial metazoans are projected to vanish by ~0.9 Gyr from the present, and all remaining metazoans—including marine taxa—are expected to disappear by ~1.0–1.1 Gyr, with an estimated uncertainty of −0.1 to +0.2 Gyr. The new discussion section contains a new section, 4.2 Reliability of future biodiversity projections.

Table 7. Estimated ages of complete extinction and 50% diversity loss for insects, tetrapods, and marine metazoans under four primary models and seven hypothetical test scenarios.

	Complete extinction age (Gyr)			Half diversity age (Gyr)		
Case	**Insect**	**Tetrapod**	**Marine metazoan**	**Insect**	**Tetrapod**	**Marine metazoan**
1. Conservative Model	0.88	0.88	0.97	0.65	0.65	0.74
2. No warming event (SRC stable, No FS)	1.02	1.02	1.12	0.65	0.65	0.74

3. No O_2 decrease (RRO stable)	0.97	0.88	0.97	0.84	0.84	0.84
4. No CO_2 decrease (RRC stable only)	0.88	0.88	0.97	0.74	0.74	0.84
5. No CO_2 decrease (RRC stable, No decrease climatic cycle)	0.88	0.88	0.97	0.74	0.74	0.84
6. No CO_2 decrease (No decrease climatic cycle only)	0.88	0.88	0.97	0.74	0.74	0.84
7. No gradual warming (RRW stable)	0.88	0.88	0.97	0.65	0.65	0.74
8. No food scarcity (No FS only)	0.97	0.97	0.97	0.65	0.65	0.74
9. Worst Anthropocene Model	0.88	0.88	0.97	0.65	0.65	0.74
10. Continuous Worst Anthropocene Model	0.88	0.88	0.97	0.65	0.65	*0.65*
11. New Evolutional Model	0.88	0.88	0.97	0.74	0.84	0.93

Underlined values indicate delays relative to the Conservative Model, while italicized values indicate earlier occurrences. Cases 2–10 are modified versions of the Conservative Model, among which Cases 2–8 represent hypothetical test scenarios that are not considered realistic.

The author often restates results (e.g., "The combined effects... will drive a substantial decline") and ventures into highly speculative territory (e.g., Section 4.3 on intelligent life strategies and Mars) without a clear framing. For example, Section 4.3, while interesting, is tangential to the core scientific findings about metazoan diversity. It risks detracting from the paper's focus and lacks the scientific support found in other sections. Thus, the author reframes result restatements as a setup for interpretation. For speculative sections, clearly label them as such and connect them directly to the model's projections.

Author reply: Deleted the restated sentences. Removed the section.

While citations are used, the discussion often uses them to support the model's assumptions rather than to contrast or synthesize the model's findings with other published work. Therefore, the author should actively engage with alternative viewpoints or models, positioning their work within the ongoing scientific conversation.

Author reply: This is written in 4.1 Characteristics of future diversity estimation in this study.

The central message that metazoans will decline after 0.4 Gyr and go extinct at 0.7 Gyr due to combined temperature, O_2, and plant crises is repeated multiple times (e.g., in 4.1, 4.1.2, 4.2, 4.4). This repetition reduces its impact. The author should simplify the main narrative, state the key conclusion clearly once, and then use the following sections to discuss different aspects of it (limitations, mechanisms, implications) without restating the conclusion verbatim.

Author reply: Done.

There is a clear copy-paste error in Section 4.4 (L. 566-574), where a whole paragraph is duplicated ("Rising Global Temperatures at Events 8–10...").

Author reply: Removed the repetition.

[Conclusion: 5.]

The second half of the conclusion goes far beyond the paper's scientific findings into policy, ethics, and futurology. The author's statements, such as "To mitigate biodiversity loss, advanced species may need to implement strategies..." and "emphasizing the urgency of proactive measures," are not conclusions derived from your model. While interesting, the author should phrase it more neutrally. The author should focus the conclusion on the scientific findings. The speculative strategies (aerosol shielding, space colonization) can be mentioned as potential consequences of the findings, but not as prescriptive "needs." Avoid language that tells the reader what is "urgent."

Author reply: Removed them.

The entire study relies on a model with significant uncertainties (as noted in comments for the discussion). The conclusion states the 0.7 Gyr timeline as a definitive result without any qualification. The author should consider adding a sentence that acknowledges these inherent uncertainties.

Author reply: Added new subsection 4.4 Uncertainties in the timing of final metazoan extinction

Earth's surface temperature is the primary factor controlling the timing of complete metazoan extinction. Consequently, uncertainties in estimating final extinction timing are directly tied to uncertainties in surface temperature. These include components such as the long-term warming trend, long-term climatic cycles (icehouse and greenhouse phases), and abrupt climate shifts.

The uncertainty associated with the long-term warming trend is estimated at −0.1 to +0.2 Gyr, based on Mello and Friaça (2019). Uncertainty from climatic cycles is ±0.1 Gyr; however, this contribution is minor at the point of complete extinction. The timing of abrupt events carries an uncertainty of ±0.03 Gyr (1σ). Additionally, differences in metazoan responses to declining O_2 and CO_2 levels are reflected in the divergence between survival durations in the Conservative and New Evolutional Models.

Therefore, the total uncertainty in the timing of final metazoan extinction, as governed by Earth's surface temperature, is estimated to range from −0.1 to +0.2 Gyr. L626

Revised to "Despite uncertainties ranging from −0.1 to +0.2 Gyr (Fig. 2 caption), all model scenarios consistently predict a long-term decline in biodiversity beginning around 0.5–0.9 Gyr, ultimately resulting in the extinction of terrestrial metazoans by approximately 0.9 Gyr and marine metazoans by approximately 1.0 Gyr." L641. Figure 2 caption. The black dashed line, adapted from Mello and Friaça (2019), represents long-term historical trends (error range: −1 to +0.2 Gyr). Added Table 7. The original estimate of 0.7

Gyr for complete metazoan extinction has been revised to 0.9 Gyr for all terrestrial metazoans and approximately 1.0–1.1 Gyr for marine metazoans in this manuscript. One major reason for this revision is the incorporation of decreasing CO_2 levels due to increased continental weathering, which influences long-term warming anomalies used to generate the orange curve in Figure 2. Another reason is that oxygen decline is not applied to short-term diversity loss, but rather to long-term biodiversity changes. Added "A key assumption is that the amplitude of long-term icehouse–greenhouse climate cycles—occurring at ~0.35–0.30 Gyr intervals (Scotese et al., 2021; Torsvik et al., 2024; Vérard, 2024)—will gradually diminish as atmospheric CO_2 declines through enhanced continental weathering; for modeling purposes, these cycles are treated as having 0.30 Gyr intervals. In contrast, major abrupt climatic perturbations capable of triggering mass extinctions are assumed to continue recurring at ~0.094 Gyr intervals, based on the mean recurrence time calculated from age data in Kaiho (2025). Importantly, the specific values chosen for these intervals do not influence the 0.1 Gyr–resolution results presented in the abstract (Fig. 2)." L73, and "ΔTc is 8 °C maximum gradually decreasing to 0 °C at 1.2 Gyr lasting till >1.5 Gyr during greenhouse periods and 0 °C during icehouse phases." L161.

The phrase "this study is the first to reveal that humanity exists at the midpoint of metazoan lifespan" makes a very strong claim in the conclusion. While it might be true, it sounds self-promoting. The most suitable place to highlight this novelty is in the Introduction and Discussion sections. The author could rephrase this to emphasize the finding itself. For example, "An interesting corollary of this timeline is that humanity appears near the midpoint of Earth's metazoan history."

Author reply: Added "An interesting implication of this timeline is that the total lifespan of metazoans on Earth is therefore estimated at 1.6–1.7 billion years—approximately 12% of Earth's projected 12-billion-year habitable lifespan. Humanity currently exists near 40% of Earth's metazoan history and about 30% of Earth's terrestrial metazoan history." L623 in the discussion section 4.3.

The main point, extinction at 0.7 Gyr, is repeated three times in a very brief text. While repetition can emphasize a point, here it limits the development of a more nuanced final message. The author can condense the key finding into one strong statement at the beginning and use the remaining space to discuss its causes and implications.

Author reply: Done.