Dear editor, 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.

Referee comment from Anonymous Referee #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: I agree with the comments. I revised words marked in blue in the attached manuscript (Kaiho Revise Marked 1).

Added lines 38-43 in the Introduction. Estimates for the end of Earth's biosphere published after 2010 vary widely. Projections based on surface temperature range from 1.0 to 5.0 Gyr (O'Malley-James et al., 2012; Rushby, 2013; Leconte et al., 2013; Wolf and Toon, 2015), while scenarios based on CO_2 depletion yield estimates of 0.84–1.08 Gyr (Rushby, 2015; Ozaki and Reinhard, 2021). Mello and Friaça (2019) suggest that biosphere collapse is unlikely before 1.5 Gyr based on thermal constraints. However, a decline in atmospheric oxygen to 1% PAL within 1.08 ± 0.14 Gyr (1σ) as predicted by Ozaki and Reinhard (2021) may lead to the earlier extinction of metazoan life.

Added lines 62-63 in the Introduction. This study builds upon previous models by integrating anthropogenic crises (Waters et al., 2011; Ceballos et al., 2015; Waters et al., 2016; Kaiho, 2022, 2023), cyclical climate rhythms, and abrupt climate events. It considers seven key factors—anthropogenic crises, long-term warming, cyclical climate rhythms, abrupt events, C_3 plant collapse, C_4 plant decline, and oxygen depletion—to project metazoan extinction over the next 1.5 Gyr. Projections are grounded in temperature and oxygen modeling, thermal tolerance limits, and observed metazoan diversity trends.

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 3.2 (Results) and 4.1 (Discussion) sections.

3.2 Metazoan lifetime estimation under four scenarios

When only the long-term warming trend driven by the gradual increase in solar luminosity is considered (Mello and Friaça, 2019), metazoans are projected to go extinct at approximately 1.3 Gyr, based on the intersection of the black dashed line with the upper boundary of GATEU90 in Figure 1. Under this scenario, surface-dwelling metazoans are expected to go extinct slightly earlier, at 1.2 Gyr, based on the same trend intersecting the upper boundary of GATES90.

When long-term cyclical fluctuations between icehouse and greenhouse phases are incorporated into the model, extinction is projected to occur at 1.2 Gyr, corresponding to the intersection of the orange line with the top of GATEU90. In this case, surface metazoans are expected to disappear by 1.0 Gyr, as indicated by the intersection with GATES90.

Incorporating average surface temperature anomalies associated with past mass extinction events further lowers the projected extinction time to 1.0 Gyr, based on the red circle's intersection with the upper boundary of GATEU90. However, actual complete extinction is expected to occur earlier, between 0.7 and 0.8 Gyr, due to compounded survival rate reductions (0.01–0.1) caused by food scarcity (FS) and oceanic anoxia. These stressors are expected to be triggered by elevated temperatures during abrupt extinction events (Events 8–10), which involve the collapse of surface metazoan populations and severe reductions in primary productivity caused by global-scale extreme warming (see Table A5).

By 0.7 Gyr, atmospheric oxygen and CO_2 levels are not anticipated to be the dominant extinction drivers. Instead, the primary cause of complete extinction is projected to be extreme surface warming, resulting from the combined effects of increased solar luminosity, long-term climatic oscillations, and large-scale volcanic activity. Therefore, the final extinction of all metazoan life is projected to occur at 0.7 ± 0.05 Gyr.

4 Discussion

4.1 Lifetime estimation

Previous studies have proposed varying estimates for the remaining lifespan of metazoan life on Earth. A 1.2 Gyr estimate has been cited as a plausible median value (Jebari and Sandberg, 2022), while 1.3 Gyr is projected based solely on the long-term warming trend driven by increasing solar luminosity (Fig. 1), and 1.1 Gyr corresponds to the point at which atmospheric oxygen is predicted to decline to 1% PAL (Ozaki and Reinhard, 2021).

In contrast, the present study estimates the total remaining metazoan lifespan at approximately 0.7–0.8 Gyr from now, which is 300 to 600 million years earlier than previous estimates. This discrepancy arises because earlier models do not account for the compounding effects of long-term cyclical icehouse–greenhouse climate phases**,** average surface temperature anomalies during mass extinction events, and cooling effects linked to mantle temperature decline.

The estimates from the current study are considered more realistic, as they incorporate all major drivers of surface temperature variability—including long-term trends, cyclical oscillations, and abrupt catastrophic events—providing a more comprehensive projection of the environmental conditions leading to metazoan extinction.

Author Reply: Revised to "Ultimately, a final extinction event—likely initiated by large-scale volcanism—will be primarily driven by extreme global warming." in lines 16-17 (Abstract). Added ", primarily driven by global warming" in line 704-705 (Conclusions). The sentence is "This scenario indicates that complete metazoan extinction is expected to occur within 0.7–0.8 Gyr, primarily driven by global warming."

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: I agree with the comments. Revised the 2.7 section in Methods: Future metazoan diversity estimation as the following section (revised parts are marked in blue). Also revised Figures 5–7 based on the revised 2.7 section.

2.7 Future metazoan diversity estimation

Future changes in metazoan diversity are influenced by the ongoing anthropogenic crisis ("event 0"), subsequent mass extinction events (events 1–11), C_3 and C_4 plant crises, and gradual oxygen depletion (see Table 2). The projected diversity of insects, terrestrial tetrapods, and marine metazoans is estimated before extinction events, immediately after, and following recovery using the equations below:

Diversity loss due to extinction event:

$$D_t = D_{t-1} \times SRC \times FSR \quad (12)$$

Diversity following recovery (after 50 Myr from the extinction event to before the next event):

$$D_{t+1} = D_t + (D_{t-1} - D_t) \times RR \quad (13)$$

Recovery Rate (RR):

$$RR = RRW \times RRO \times RRP \quad (14)$$

In these equations, Dt represents metazoan diversity at time step *t*, corresponding to the level immediately following an extinction event. Dt−1 denotes the diversity prior to the extinction event, while Dt+1 reflects the diversity after the recovery phase, measured at the midpoint between extinction events. SRC is the Survival Rate associated with climate-driven crises, including mass extinctions and C_3–C_4 plant collapses. *FSR* is the Food Scarcity Rate, reflecting the impact of the collapse of plants and primary producers. The total Recovery Rate (RR) is calculated as the product of three components: RRW (recovery from gradual warming), RRO (recovery from progressive oxygen decline), and RRP (recovery from decreased primary productivity due to CO_2 reduction).

These equations are applied sequentially across time steps from event 0 through event 16, encompassing extinction episodes, recovery phases that conclude at the midpoint between events, and the subsequent interval leading up to the next extinction event (see Table A5).

2.7.1 Survival Rate associated with Climate change (SRC)

Survival Area Rate (SAR) is rate of land and ocean area where metazoans survive in all land and ocean area (km2/km2). When extinction occurred in 0–10, 0–20, 0–30, 0–40, 0–50, 0–60, 0–70, 0–80, and 0–90° latitudes by warming, SAR values are defined as 0.83, 0.66, 0.50, 0.36, 0.24, 0.14, 0.06, 0.02, 0.00, respectively, under the same rate of land and ocean in those latitudes. The rates SAR are decided by only temperature 46 °C using Figure 2. SAR_S is Survival Area Rate for St and Sw metazoans, SAR_U and SAR_D are Survival Area Rate for U and D metazoans, respectively. These SAR are obtained from GATES, GATEU, and GATED in Figure 2.

The SRC (survival rate by climates) is calculated as:

$$SRC_T = 0.95 \times SAR_S + 0.05 \times SAR_U \quad (15)$$

$$SRC_M = 0.67 \times SAR_S + 0.33 \times SAR_D \quad (16)$$

Here, SRC_T and SRC_M represent the terrestrial and marine SRC, respectively. The coefficient 0.05 corresponds to the proportion of subterranean metazoan families among all terrestrial metazoan families (15 out of 315), based on mammalian lineage data (Recknagel & Trontelj, 2021; Benton, 2010). The remaining 0.95 represents superterranean (surface-dwelling) taxa. The coefficient 0.33 reflects the proportion of deep-sea fish families among all marine fish families, based on an estimated 6% of teleost species restricted to depths >200 m (Miller et al., 2022), with scaling applied via the species-genus-family extinction relationship from Kaiho (2022). The remaining 0.67 applies to surface-dwelling marine taxa. Equations (15) and (16) are used for modeling extinction scenarios during Events 5–16.

SAR_D is influenced by both temperature and dissolved oxygen levels. Elevated surface temperatures reduce oxygen concentrations in deep water, a process linked to deep-sea extinctions during the end-Permian and end-Cenomanian anoxia–euxinia events, despite elevated atmospheric O_2 (e.g., Sun et al., 2012; Kaiho et al., 2013, 2016a). High surface temperatures can cause extinction in both surface and deep-water taxa. Although deep water temperatures are lower than those at the surface, the greatest thermal anomalies occur in surface waters, while deep-water temperatures remain relatively constant throughout the water column. Consequently, SAR_D is assumed to approximate SAR_S.

Thus, for Events 5–6, 8–16, and all non-events after Event 8 (excluding the interval between Events 9 and 10), SAR_D is set equal to SAR_S, as these intervals are characterized by global surface temperatures comparable to or exceeding those of the end-Permian.

The dominant climate driver for mass extinction varies by event. Events –5 to 4 involve both warming and cooling phases, while Events 5–16 are exclusively warming-driven, corresponding to the yellow–orange shaded zone in Figure 1.

For Event 0 (the Anthropogenic Crisis), the maximum SRC values are set at 0.95 for insects, 0.70 for terrestrial tetrapods, and 0.90 for marine metazoans. These values reflect a worst-case scenario involving full-scale nuclear war, combined with moderate anthropogenic pollution, deforestation, and global warming (Kaiho, 2023). In the absence of nuclear conflict, SRC is assumed to be 1.0 for all groups. For Events 1–4 and 7, SRC values are 0.81 for insects, 0.63 for terrestrial tetrapods, and 0.74 for marine metazoans, based on average extinction percentages reported in Tables A3 and A4.

In events 5 and 6 where global average surface temperatures reach 38–39 °C in Figures 2a and 2c. The 38 °C and 39 °C correspond to GATES40 and 50 (SAR_S: 0.36 and 0.24) in Figures 2a and 2c, and GATEU00 and GATEU10 (SAR_U: 1.00 and 0.83) in Figure 2b. The both temperatures are lower than GATED showing 48°C (Fig 2d). Using equations 15 and 16, the SRC values are:

In Events 5 and 6, global mean surface temperatures reach 38–39 °C (Figures 2a, 2c). These correspond to GATES40 and GATES50 (SARS: 0.36 and 0.24), and to GATEU00 and GATEU10 (SARU: 1.00 and 0.83) in Figure 2b. Both values are below the stable GATED threshold of 48 °C (Figure 2d). Applying equations (15) and (16):

Event 5:

$SRC_T = 0.95 \times 0.36 + 0.05 \times 1.00 = 0.39$

$SRC_M = 0.67 \times 0.36 + 0.33 \times 1.00 = 0.57$

Event 6:

$SRC_T = 0.95 \times 0.24 + 0.05 \times 0.83 = 0.27$

$SRC_M = 0.67 \times 0.24 + 0.33 \times 1.00 = 0.49$

These values are listed in Table 2.

In Events 8–10, global surface temperatures rise to 43–45 °C (Figures 2a, 2c). At 43 °C, GATES90 is reached, resulting in complete extinction of surface-dwelling metazoans (SARS = 0). The corresponding

SARU values, 0.50 and 0.30, are based on GATEU30 and GATEU45 (Figure 2b). GATED remains at 48 °C, so SARD = 0. Using equations (15) and (16):

Event 8:

$SRC_T = 0.95 \times 0 + 0.05 \times 0.50 = 0.025$

Events 9 and 10:

$SRC_T = 0.95 \times 0 + 0.05 \times 0.30 = 0.015$

Events 8–10:

$SRC_M = 0.67 \times 0 + 0.33 \times 0 = 0$

These SRC values are also summarized in Table 2.

2.7.2 Food Scarcity Rate (FSR)

In addition to direct climatic impacts, food scarcity significantly contributes to extinction risk. As plants and primary producers collapse, only organisms capable of surviving on bacterial biomass or sedimentary organic matter—along with their predators—will remain. Consequently, an additional decline in survival rate, quantified as the Food Scarcity Rate (FSR), is expected during abrupt extinction events such as Events 8–10.

These events are characterized by the extinction of superterranean and surface-water (SS) metazoans and severe reductions in primary productivity due to sunlight loss—conditions common in major mass extinction scenarios (see Fig. 1). A low FSR value of 0.01 reflects survival through alternative nutritional pathways, including hydrothermal vent ecosystems and bacterial-based underground food sources (Cosson and Soldati, 2008; Miroshnichenko, 2004; Kelley et al., 2005).

Conversely, a high FSR value of 0.1 represents an optimistic estimate, assuming evolutionary adaptation of primary producers to extreme temperatures, allowing some limited ecosystem function to persist. This range (0.01–0.1) is applied to adjust survival estimates in scenarios where abrupt collapse of food webs occurs due to light inhibition and temperature stress.

2.7.3 Recovery Rate by Warming (RRW)

The Recovery Rate by gradual Warming (RRW), applied outside of abrupt extinction events, is calculated using the same structure as Equations (15) and (16), but based on temperature anomalies associated with gradual climate changes. These temperature anomalies are derived from Figure 2.

The RRW is calculated separately for terrestrial and marine metazoans using the following equations:

$$RRW_T = 0.95 \times SAR_S + 0.05 \times SAR_U \quad (17)$$

$$RRW_M = 0.67 \times SAR_S + 0.33 \times SAR_D \quad (18)$$

Here, RRW_T and RRW_M denote the recovery rates for terrestrial and marine metazoans, respectively. The coefficients reflect the relative contributions of surface and subsurface habitats, consistent with SRC calculations in earlier sections.

2.7.4 Recovery Rate by Oxygen decline (RRO)

The Recovery Rate by Oxygen decline (RRO) is calculated separately for terrestrial and marine metazoans, reflecting projected atmospheric O_2 levels over the next 1.0 Gyr. The RRO varies across time intervals and is defined by the following equations:

For terrestrial metazoans (RRO_T):

During the next 0.5 Gyr: $RRO_T = 1.0$ (19)

During the next 0.5–0.8 Gyr: $RRO_T = 2.67 - 3.33T$ (20)

During the next 0.8–1.0 Gyr: $RRO_T = 0.0$ (21)

For marine metazoans (RRO_M):

During the next 0.5 Gyr: $RRO_M = 1.0$ (22)

During the next 0.5–0.8 Gyr: $RRO_M = 2 - 2T$ (23)

During the next 0.8–1.0 Gyr: $RRO_M = 1.84 - 1.80T$ (24)

In these equations, T is the numerical time variable in Gyr, ranging from 0.5 to 1.0. RRO_T and RRO_M represent the recovery rates for terrestrial and marine metazoans, respectively. These values are derived from oxygen level projections by Ozaki and Reinhard (2021).

Atmospheric oxygen levels are projected to steadily decline over the next 1.1 Gyr. Beginning at approximately 1.0 PAL around –0.1 Gyr (i.e., present time), O_2 levels are expected to drop to ~0.5 PAL (median: 0.3–0.7) by 0.5 Gyr. This decline continues to ~0.3 PAL (median: 0.07–0.5) at 0.8 Gyr, followed by a rapid collapse to ~0.01 PAL between 1.0 and 1.1 Gyr.

These projections inform the modeled RRO values and are used in conjunction with observed relationships between atmospheric O_2 levels and metazoan/plant diversity (Fig. 3) to assess the impact of oxygen depletion on biodiversity trajectories throughout Earth's future.

2.7.5 Recovery Rate by Primary productivity (RRP)

A molecular-level investigation of a C_3 plant's response to low CO_2 concentrations (100 ppm compared to the typical 380 ppm) revealed that reduced CO_2 levels lead to a significant decline in biomass productivity (Li et al., 2014). In the future, such low CO_2 conditions are projected to occur at approximately 0.5 Gyr (ranging from 0.4 to 0.65 Gyr), despite rising surface temperatures driven by increasing solar luminosity. This decline in atmospheric CO_2 is expected to cause a gradual reduction in net primary productivity (NPP), ultimately contributing to long-term decreases in metazoan diversity.

Approximately 40 million years after the extinction of C_3 plants, C_4 plants are expected to evolve into tree-like forms. This evolutionary transition is anticipated to support the diversification of metazoans that rely on such vegetation, paralleling the Devonian rise of terrestrial plant ecosystems. These recovering metazoan groups are expected to originate from species formerly dependent on C_3 plants. The Recovery Rate by primary Productivity (RRP) in this context is estimated to range from 0.3 to 0.8, reflecting the evolutionary and ecological challenges in re-establishing complex, tree-supported food webs from C_4 vegetation. This recovery event is centered at 0.4 Gyr, based on a temporal uncertainty of ±0.2 Gyr (Table 2).

Although oceanic primary producers are predominantly phytoplankton, both C_3 and C_4 photosynthetic pathways coexist in marine environments (Reinfelder et al., 2000, 2004). To approximate the effect of terrestrial plant crises on marine metazoan diversity, equivalent reduction and recovery values are provisionally applied to marine systems, mirroring those used for terrestrial tetrapods under two modeled scenarios.

For Events 8–10, which involve abrupt primary productivity collapse due to sunlight reduction, RRP is estimated between 0.1 and 0.3, representing an intermediate range between C_3 and C_4 plant crises.

The C_4 plant crisis is expected to occur at approximately 0.97 ± 0.2 Gyr, aligning closely with Event 11. At this stage and beyond, RRP values decline to between 0.01 and 0.1, as NPP is assumed to approach zero. Under such conditions, only UD metazoans—those subsisting on bacteria, detritus, or residing in deep-sea hydrothermal ecosystems—would persist (Cosson and Soldati, 2008; Miroshnichenko, 2004; Kelley et al., 2005). This sharp reduction in RRP reflects the critical dependence of most metazoans on photosynthetically sustained food webs.

Specific comments

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

Author Reply: Done

• _L. 32: Can you shortly explain what C_3 and C_4 plants are?

Author Reply: Revised to “The reduction in CO_2 will affect the photosynthesis of two major plant groups—C_3 and C_4 plants—differently, due to their distinct photosynthetic pathways. C_4 plants generally exhibit higher photosynthetic efficiency under hot and dry conditions, making them more resilient to low CO_2 levels than C_3 plants.”

• _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: Revised to section 2.5.2.

• _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”.

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

Author Reply: Revised to “Projections of future atmospheric oxygen levels and marine and terrestrial metazoan diversity were informed by records from the Paleozoic biodiversity maximum.”.

• _L. 98: What is PAL?

Author Reply: The phrase “present atmospheric levels (PAL)” has already written in the first paragraph of Introduction section.

• _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”

• _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: Moreover, the emergence of terrestrial metazoans likely required elevated oxygen levels due to their dependence on a protective ozone layer that shields the surface from harmful short-wavelength ultraviolet radiation. These insights form the basis for further discussion in Section 2.4.

• _L. 110-115: What were the main reasons for mass extinction during these events? Author Reply: Added the following sentence: The primary drivers of these mass extinctions were large-scale volcanic events, with the notable exception of the end-Cretaceous extinction, which was caused by a meteoroid impact (Kaiho, 2025).

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

Author Reply: Yes, I revised it to orange.

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

Author Reply: Revised to “five major mass extinctions” in line 169. Five major mass extinctions were defined in Introduction section.

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

Author Reply: Yes, it was.

• _L. 163: What is sill?

Author Reply: Added “(a tabular sheet intrusion from magma that has intruded between older layers of sedimentary rocks)” in line 185.

• _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.

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

Author Reply: Revised to "The model presented in Figure 2a estimates extinction thresholds for St metazoans (i.e., surface-dwelling terrestrial animals) based on oceanic climate regions on land, as these regions generally experience milder climates compared to continental interiors."

• _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 "Baseline warm climate gradient: Oblique lines with a 15 °C gradient from equator to pole are drawn to represent warm Earth conditions (e.g., the late Paleocene–early Eocene and mid-Cretaceous hothouse periods), which are relevant for modeling extinction under future warming scenarios (Zhang et al., 2019; Burgener et al., 2023). These lines intersect the 46 °C tolerance points (thick oblique lines in Figure 2a)."

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

Author Reply: This adjustment uses modern reference data from warm coastal cities such as Shanghai (~30°N) and Singapore (~0°N) (Weather Spark, https://weatherspark.com) (dashed oblique lines in Figure 2a).

• _L. 201: Same as l. 191 and l. 196: Why do you use data from warm coastal cities? Author Reply: Revised to "This adjustment uses modern reference data from warm coastal cities such as Shanghai (~30°N) and Singapore (~0°N) (Weather Spark, https://weatherspark.com), as indicated by the dashed oblique lines in Figure 2a, to determine the extinction threshold."

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

Author Reply: Section 2.6.3 in line 267.

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

Author Reply: Revised to "where LT (Local Temperature) is the latitude-dependent adjustment from LMMT to LAT." in line 260.

• _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: Revised this section. Also revised the title to Survival Rate associated with Climate change (SRC).

• _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: The different SRC in events 5 and 6 and event 7 is due to a long-term greenhouse period and a long-term ice house period, respectively. Added the calculation in lines 343-347.

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

Author Reply: SAR is rate of land area where metazoans survive in all land area (km^2/km^2). Added "Survival Area Rate (SAR) is rate of land and ocean area where metazoans survive in all land and ocean area (km^2/km^2). When extinction occurred in 0–10, 0–20, 0–30, 0–40, 0–50, 0–60, 0–70, 0–80, and 0–90° latitudes by warming, SAR values are defined as 0.83, 0.66, 0.50, 0.36, 0.24, 0.14, 0.06, 0.02, 0.00, respectively, under the same rate of land and ocean in those latitudes. The rates SAR are decided by only temperature 46 °C using Figure 2." in line 302-305.

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

Author Reply: I wrote coefficient 0.95, 0.67, 0.05, 0.33 instead of these abbreviation in these equations (15, 16) in lines 309-310. The following paragraph explains these coefficients.

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

Author Reply: Added "Survival Area Rate (SAR) is rate of land and ocean area where metazoans survive in all land and ocean area (km^2/km^2). When extinction occurred in 0–10, 0–20, 0–30, 0–40, 0–50, 0–60, 0–70, 0–80, and 0–90° latitudes by warming, SAR values are defined as 0.83, 0.66, 0.50, 0.36, 0.24, 0.14, 0.06, 0.02, 0.00, respectively, under the same rate of land and ocean in those latitudes. The rates SAR are decided by only temperature 46 °C using Figure 2." in line 302-305.

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

Author Reply: Added "High surface temperatures can cause extinction in both surface and deep-water taxa. Although deep water temperatures are lower than those at the surface, the greatest thermal anomalies occur in surface waters, while deep-water temperatures remain relatively constant throughout the water column." in lines 320-323.

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

Author Reply: Revised to "FSR is the Food Scarcity Rate, reflecting the impact of the collapse of plants and primary producers." in lines 295-296.

Added the following explanation in lines 364-371.

These events are characterized by the extinction of superterranean and surface-water (SS) metazoans and severe reductions in primary productivity due to sunlight loss—conditions common in major mass extinction scenarios (see Fig. 1). A low FSR value of 0.01 reflects survival through alternative nutritional pathways, including hydrothermal vent ecosystems and bacterial-based underground food sources (Cosson and Soldati, 2008; Miroshnichenko, 2004; Kelley et al., 2005).

Conversely, a high FSR value of 0.1 represents an optimistic estimate, assuming evolutionary adaptation of primary producers to extreme temperatures, allowing some limited ecosystem function to persist. This range (0.01–0.1) is applied to adjust survival estimates in scenarios where abrupt collapse of food webs occurs due to light inhibition and temperature stress.

• _L. 275: And the other events?

Author Reply: Added the followings in lines 335-358.

In events 5 and 6 where global average surface temperatures reach 38–39 °C in Figures 2a and 2c. The 38 °C and 39 °C correspond to GATES40 and 50 (SAR_S: 0.36 and 0.24) in Figures 2a and 2c, and GATEU00 and GATEU10 (SAR_U: 1.00 and 0.83) in Figure 2b. The both temperatures are lower than GATED showing 48°C (Fig 2d**).** Using equations 15 and 16, the SRC values are:

In Events 5 and 6, global mean surface temperatures reach 38–39 °C (Figures 2a, 2c). These correspond to GATES40 and GATES50 (SARS: 0.36 and 0.24), and to GATEU00 and GATEU10 (SARU: 1.00 and 0.83) in Figure 2b. Both values are below the stable GATED threshold of 48 °C (Figure 2d). Applying equations (15) and (16):

Event 5:

$SRC_T = 0.95 \times 0.36 + 0.05 \times 1.00 = 0.39$

$SRC_M = 0.67 \times 0.36 + 0.33 \times 1.00 = 0.57$

Event 6**:**

$SRC_T = 0.95 \times 0.24 + 0.05 \times 0.83 = 0.27$

$SRC_M = 0.67 \times 0.24 + 0.33 \times 1.00 = 0.49$

These values are listed in Table 2.

In Events 8–10, global surface temperatures rise to 43–45 °C (Figures 2a, 2c). At 43 °C, GATES90 is reached, resulting in complete extinction of surface-dwelling metazoans (SARS = 0). The corresponding SARU values, 0.50 and 0.30, are based on GATEU30 and GATEU45 (Figure 2b). GATED remains at 48 °C, so SARD = 0. Using equations (15) and (16):

Event 8:

$SRC_T = 0.95 \times 0 + 0.05 \times 0.50 = 0.025$

Events 9 and 10:

$SRC_T = 0.95 \times 0 + 0.05 \times 0.30 = 0.015$

Events 8–10:

$SRC_M = 0.67 \times 0 + 0.33 \times 0 = 0$

These SRC values are also summarized in Table 2.

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

Author Reply: Revised to "Although oceanic primary producers are predominantly phytoplankton, both C_3 and C_4 photosynthetic pathways coexist in marine environments (Reinfelder et al., 2000, 2004)." in lines 414-415.

• _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: Revised to "The C_4 plant crisis is expected to occur at approximately 0.97 ± 0.2 Gyr, aligning closely with Event 11. At this stage and beyond, RRP values decline to between 0.01 and 0.1, as NPP is assumed to approach zero. Under such conditions, only UD metazoans—those subsisting on bacteria, detritus, or residing in deep-sea hydrothermal ecosystems—would persist (Cosson and Soldati, 2008; Miroshnichenko, 2004; Kelley et al., 2005). This sharp reduction in RRP reflects the critical dependence of most metazoans on photosynthetically sustained food webs." in lines 420-424.

• _L. 304: What exactly is numerical age?

Author Reply: Revised to "In these equations, T is the numerical time variable in Gyr, ranging from 0.5 to 1.0."

• _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: Moved to section 2.5.5.

• _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 "Climate Phases B–E are likely to be initiated by abrupt climate disturbances caused by large volcanic eruptions or meteorite impacts occurring during greenhouse intervals." In lines 214-215."

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

Author Reply: Revised to "In both the Min and Max Cases, during Events 1–4 (occurring between 0.03 and 0.40 Gyr into the future), biodiversity will decline sharply from current levels of 610 insect families, 315 terrestrial tetrapod families, and 950 marine metazoan families to 494, 198, and 703 families, respectively. These losses are followed by full recovery to the present number of families (Fig. 5).

In the NC Min Case, Event 0 (the Anthropogenic Crisis) results in reduced survival, with 580 insect families, 221 terrestrial tetrapod families, and 855 marine metazoan families remaining, followed by recovery to current diversity levels (Fig. 5).

However, if the recovery rate after Event 0 is zero—as modeled in the NCC Min Case—biodiversity continues to decline due to sustained anthropogenic impacts on the biosphere. In this scenario, even during non-extinction intervals, the surviving numbers of families are projected to remain at 580 for insects, 221 for terrestrial tetrapods, and 855 for marine metazoans (Fig. 6). The NCC Max Case also results in equivalent proportional reductions compared to the Max Case."

• _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 diamond symbols denote temperatures before mass extinctions."

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 "Impact on metazoans" in Figure 1.

• 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 indicate their approximate diversity and corresponding oxygen levels, whereas silhouettes of terrestrial plants indicate only corresponding oxygen levels."

• 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. Revised Aftermath warming to Warming.

• _L. 720 and 725: before or after?

Author Reply: Revised to "Underlined and double underlined numbers indicate values corresponding to 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: No, the underlined numbers occur just after major mass extinction events.

Technical corrections

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

Author Reply: Revised to "have triggered past mass extinctions"

• _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: LMmMT

Done

• _L. 213: 2.5 meters

Done

• _L. 222: GATES values are common equal

Done

• _L. 237: where, D_t represents

Done

• _L. 324: 1 meter

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: illustrates

Done

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

Done

• _Fig. 2:

- Atmospheric oxygen level relative to for present atmospheric level
- 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 anomalyies 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