Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality.

11th Feb 21

Dear Dr Neubauer,

Please allow me to apologise for the delay in sending a decision on your manuscript titled "Current extinction rate in fresh water exceeds by far that of late Cretaceous mass extinction". It has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to
• address these criticisms (that is, either to incorporate the suggestions or provide a compelling argument why the point made by the reviewer is not valid, or relevant to the editorial threshold as outlined below)
AND
• meet our editorial thresholds as outlined below,

then we would be happy to look at a substantially revised manuscript. However, please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

In the following, we list our main editorial thresholds:

Provide a compelling case that extinction rates in European freshwater gastropods during the K-Pg event have been greatly underestimated and place these toned-down conclusions firmly in the context of what we know about other continents

Either remove your comparisons between modern and ancient extinction rates or ensure that they are fully supported by robust and rigorous re-analyses which take into account the limitations of comparisons between these two types of data set, as outlined by Reviewer #1

In addition, please supply point-by-point responses to all the reviewers' comments.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter) and any completed checklist:

[link redacted]

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

Please do not hesitate to contact me if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Joe Aslin

Associate Editor,
Communications Earth & Environment
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EDITORIAL POLICIES AND FORMAT

If you decide to resubmit your paper, please ensure that your manuscript complies with our editorial policies and complete and upload the checklist below as a Related Manuscript file type with the revised article:

Editorial Policy Policy requirements

For your information, you can find some guidance regarding format requirements summarized on the following checklist:(https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Neubauer et al. present an assessment of the severity of the Cretaceous-Paleogene extinction in

fresh water gastropods, and compare it with projections of extinction rates in the next decades and centuries. The conclusion is that current/future extinction of freshwater gastropods is and will be ~1000 times as severe as the K-Pg one. The methodologies applied seems robust for each of the contexts used: the K-Pg and current/future gastropods depletion. Overall, the manuscript is well written and the hypothesis feel presented. However I have a fundamental concern around how K/Pg and current extinctions are compared.

In this study, extinction estimates from occurrence data and extinction estimates from current IUCN Red List risk categorizations are put one in front of the other like they are comparable. And they are far from comparable. Many factors render this one an unfair comparison. IUCN lists most of current diversity, even relic species with tiny geographic ranges, or those with low population densities. In fact, having a tiny geographic ranges and low population densities are good candidate features ensuring a given species ranks high in extinction risk. But also, it is the case that these species are very unlikely to leave abundant fossil remains that will be preserved, exposed and collected 66 million years into the future (assuming there are paleontologist in that future).
What I mean is that, in the same way that we take sampling biases into account when estimating extinction rates from fossils, Neubauer et al. should take sampling biases into account in the current+future extinction models. This is specially interesting given that their paleo-derived extinction curve shows a dramatic increase in extinction in the last 5 million years. So the key question is: acknowledging that species higher in the IUCN rank will most probably never make it as fossils, how much will future extinction departure from the severe extinction peak estimated for the last 3 million years (~0.8 E/MSY)?

Because “today” we see (and the IUCN evaluates) the results, not only of human activities, but those of this Quaternary extinction peak the most severe in the last 60 million years. Importantly, species high up in IUCN risk categories would already appear as extinct if a paleontologists would conduct PyRate with today’s occurrences 65 myrs into the future. Thus the first step for a fair comparison is to use IUCN data in a way that accounts for a decreasing sampling probability with higher extinction risk.

Further issues obscure a straightforward comparison. Paleontological species are not comparable to current species. Many living species would not be differentiated based on their paleontological remains. Current diversity, and thus E/MSY units, are not comparable either. This is a tricky problem, Barnosky et al. 2011 suggest to clump living species into genera for a fair comparison.

So, for such a fair comparison, I think the authors should at least address these two facets. They must aggregate living species into genera first (or some other and less straightforward grouping into mosphospecies), and then subject their IUCN to a sampling downgrading. This could be added to the risk categories transition model. For example, advances in this rank will entail an exponential decrease in sampling probability, bearing in mind that not even all widespread species leave fossils… Of course, current categories should also be linked to this exponential decrease in sampling probability and species should be resampled from tis probability of being sampled for current and future estimates of extinction. This means that as we advance in LC, NT, VU, EN, CR and EW, these should see a dramatic decrease of the odds of being included in the analyses. If DD and NE species did not make it to the Red List, we can assume that they would have never made it to the fossil record.

Then use all this to ask whether the Quaternary extinction peak we are surfing right now will get

significantly worse and we should add another shift/peak in the extinction curve of Extended Data Fig. 2.

Reviewer #2 (Remarks to the Author):

This paper has been based on the authors extensive knowledge on European Mesozoic and Cenozoic freshwater gastropods.
I fail to find any major errors in their methodology, their data and their conclusions as well as in their basic hypothesis that the coming 6th mass-extinction in European freshwater gastropods may be worse than the 5th mass-extinction.

Therefore, this paper responds to all requirements to be accepted for publication.I do however retain a single question: namely can or should a global extinction event in the future be compared to a global extinction event in the past, based on the evolution of the gastropod fauna of a single continent from the Late Mesozoic to the present?

In my opinion, the authors should at least provide some arguments why specifically Europe has been selected as a pars pro toto. For this single-continent-approach raises several issues:
- (1) in the period under consideration (Jurassic to Pleistocene), Europe was not isolated but joined with either N. America or with Asia or with both. At some points in the geological history, it may be possible to speak of a distinct European malacofauna, on others it is not so evident.
- (2) in N. America (Hartman et al., 2002, Justham, 2008, Hartman, 2015) and in SE Asia (see e.g. Yu et al., 2021), the fossil gastropod records of the Cretaceous-Paleogene transition are better preserved than in Europe. Though I could be mistaken, I do not have the impression that the shift in species composition between the end-Cretaceous and the Early Paleogene was so dramatic on these continents as the one based in the present paper on European data.
- (3) In the fossil records of other continents, the most marked difference in the composition of the freshwater molluscan fauna before and after the 5th mass-extinction, seems to be the shift from assemblages dominated by or often exclusively consisting of bivalves to assemblages consisting mainly or exclusively out of freshwater gastropods.
- (4) the number of European localities/assemblages of Cretaceous age is <40. Why localities/assemblages of Jurassic age, i.e. predating the K/P event > 100 My, have also been sampled, remains unclear to me.

In conclusion, if feel that the authors need to provide a rationale why the effects of two world wide mass extinctions are compared on the basis of the effects on the freshwater gastropods of the European continent, though there exists ample evidence that the effects of the K/T extinction were not identical on all continents.

Reviewer #3 (Remarks to the Author):

The authors analyse extinction rates on fossil freshwater gastropods from Europe, from the late Cretaceous to the Pleistocene-Holocene, and extinction rates on extant freshwater molluscs of Europe based on the status information on the IUCN Red List. The objective is clear, and the method

is well explained, but some statements should be revised.

The major issue that I found (see further comments on manuscript pdf file) is the concept of mass extinction that is used along all the paper. The authors claim that the freshwater fauna was affected by the 5th mass extinction in a larger rate than traditionally accepted (from a ~ 20% to a ~ 90%), and that their results can prove that we are now having a 6th mass extinction. Both statements possibly may be true, but they cannot be fully demonstrated with this data, that comprises only freshwater gastropods from Europe. To characterise a mass extinction, it must be considered biota from all over the world, and Europe is a small part of the continental areas on Earth. So, the results cannot be used in a straight form as a proxy to extrapolate these results for the rest of the planet (please, see comments on pdf file).

Besides, it would be useful to pay more attention to regional extinction events and species recovery rates during the climate changes over the Quaternary, as they probably are more alike to the present climate change than the extinction event in the K-Pg, where paleoclimatological and paleogeographical configuration were different from present.

In summary, this paper is important to call for a heads up for conservation of freshwater ecosystems of Europe, as extinction rates in freshwater gastropods are truly alarming, and that implies a modification in all the ecosystems. But, those results cannot be extrapolated and call them proof of a mass extinction, because a world-scale project, with data from other continents, (especially those with biodiversity hotspots) must be compared in order to do such statements.

Current extinction rate in fresh water exceeds by far that of late Cretaceous mass extinction

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Abstract

The 5th mass extinction event at the Cretaceous–Paleogene boundary 66 million years (Myr) ago eradicated three quarters of marine and terrestrial species globally. Previous studies based on vertebrates suggest that freshwater biota were much less affected. A newly assembled freshwater gastropod time series shows a severe underestimation of how these biota were impacted during the 5th mass extinction event. Extinction rates increased by more than one order of magnitude resulting in the extinction of 92.5% of all species. The extinction phase lasted 5.4 Myr and was followed by a recovery period of 6.9 Myr. Comparing these findings to estimates of the current biodiversity crisis suggests even more severe extinction risks for freshwater biota today. Our study indicates that, unless substantial conservation effort is directed to these ecosystems, we are heading towards a 6th mass extinction within the millennium, with a severe impact to freshwater biota for millions of years to come.

Keywords: Cretaceous–Paleogene extinction event, sixth mass extinction, diversification dynamics, freshwater gastropods

Introduction

Biodiversity in freshwater ecosystems is disproportionally high: while only covering 1% of the Earth's surface, they account for about 10% of the global species richness[1]. These environments and their biota provide invaluable ecosystem services sustaining human health, nutrition and fresh water supply[2–3].

Freshwater ecosystems and their biota worldwide are currently experiencing massive deterioration[1,4–10]. In many cases, regional species richness and individual abundances are in decline and extinction rates are alarmingly high[11–14]. Human impact is widely perceived as the main cause for this decline, either directly through habitat degradation or destruction or indirectly via global warming, eutrophication, pollution or invasive species[3,11,15,16].

The current biotic crisis is widely considered the onset of a major extinction event, the so-called '6th mass extinction'[17,18]. It resembles in several aspects the 5th mass extinction at the Cretaceous–Paleogene (K–Pg, formerly K–T) boundary 66 million years (Myr) ago. Both biotic crises are in geological timescales catastrophic events – an asteroid impact in the end-Cretaceous versus human impact during the Anthropocene, both paired with a steep rise in CO_2 and global temperature[19–24].

While globally 76% of all species are estimated to have gone extinct during the K–Pg event[17], some estimates of diversity loss in freshwater species amount to only 10–22%[25]. These comparably low numbers are exclusively based on the vertebrate fossil record. Vertebrates make up around 15% of species diversity in today's freshwater habitats[26], and this low proportion may not warrant general conclusions about the freshwater biota as a whole. The stark discrepancy between the suggested low

impact of the 5th mass extinction event and the current, alarmingly high extinction rates and risks for species living in fresh water calls for a reassessment of the K–Pg event beyond freshwater vertebrates.

Freshwater gastropods provide a useful model taxon to assess extinction and diversity recovery. They are among the most diverse groups of animals in fresh water ecosystems today[26,27] and have one of the best-preserved fossil records[28,29]. They inhabit nearly all freshwater habitats worldwide and have evolved different lifestyles, trophic levels and reproductive strategies[28]. Moreover, current threats and their response to climate change are well understood and representative of the general threats facing freshwater biodiversity as a whole[10,27,29–33].

To evaluate the effects of the 5th mass extinction event on freshwater biota we compiled and analyzed the European fossil record of freshwater gastropods comprising 3,127 species to assess the magnitude, duration and dynamics of extinction and of the diversity rebound across the K–Pg boundary. Considering the similarity of that extinction event with the current biodiversity crisis in terms of its catastrophic nature combined with global warming, we use the results from our analyses to outline/predict the pathway of the current crisis. For doing so, we use a recently developed approach based on species conservation status obtained from the IUCN Red List[34] to infer the magnitude and rate of extinction in Europe's extant freshwater gastropod fauna[12,35]. This allows us to evaluate the predicted loss of freshwater gastropod biodiversity in the near future under a Business-as-Usual Scenario[22].

Results

We obtained speciation and extinction times for the fossil record of freshwater gastropods through a joint inference of speciation, extinction and preservation rates from 24,759 fossil occurrences covering approximately 200 Myr (Extended Data Fig. 1, Supplementary Data 1). The reconstructed species richness trajectory shows a slow evolution throughout the Mesozoic, with only two notable peaks at the Jurassic/Cretaceous boundary and in the Late Cretaceous (Fig. 1a). Diversity drops at the end of the Cretaceous, with on average 92.5% (88.0–94.7%) of all species and 9.5% (3.5–15.8%) of all genera going extinct (Fig. 1b). Species richness recovered c. 7–8 Myr later to Late Cretaceous levels and reached a plateau in the Eocene (c. 45–30 Myr ago). Following a decline in the Oligocene, diversity peaked in the Neogene, paralleling major radiations in several long-lived lakes in the middle and late Miocene[29,37].

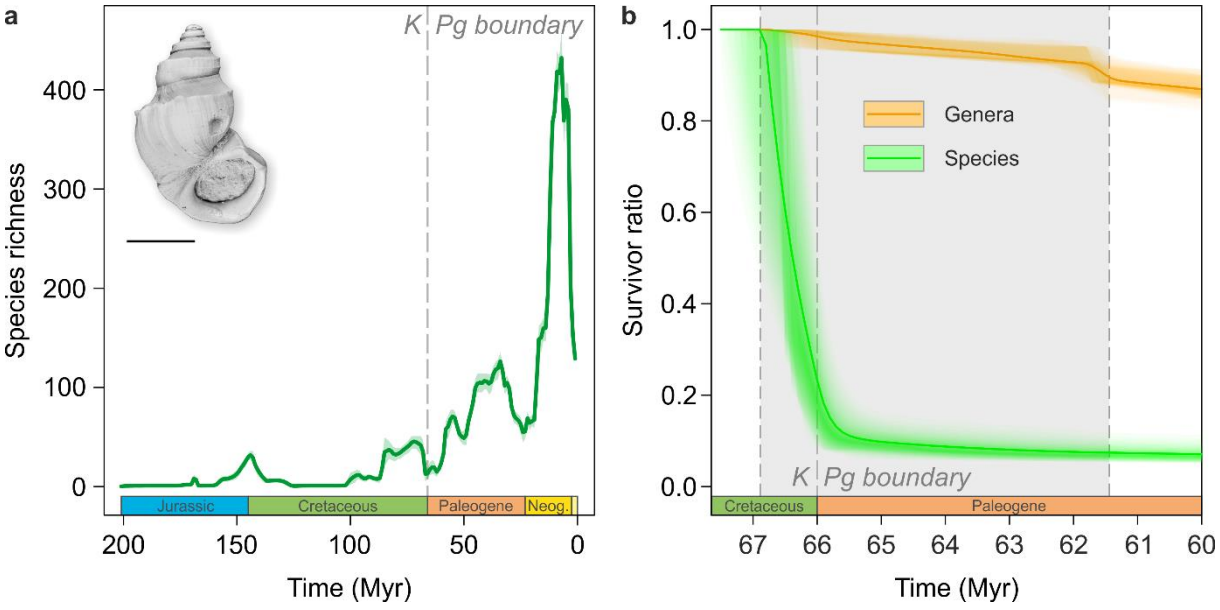

Fig. 1 | Diversity of European freshwater gastropods through time. a, Inferred species richness from the Jurassic to the Pleistocene based on our diversification analysis. Shown are the mean richness and the 95% highest posterior density interval, as well as a fossil representative of the Late Cretaceous, *Pyrgulifera armata* (Matheron, 1843) from the Santonian/Campanian of Hungary (photo M. Harzhauser, scale bar = 1 cm; after Bandel & Riedel[36]). **b**, Survivor ratio of species and genus richness before and after the extinction event (gray bar), which is marked by shifts in the extinction rate (gray lines). By the end of the extinction event, 92.5% of all freshwater gastropod species and 9.5% of the genera had gone extinct.

Both speciation and extinction rates are highest at the K–Pg boundary, exceeding the previous levels by more than one order of magnitude (Fig. 2). Earlier speciation rate peaks at the Early–Late Cretaceous transition (100.5 Myr ago) and in the Late Cretaceous (85 Myr ago) are lower and characterized by high uncertainty (large 95% credible intervals). The extinction rate remains constant throughout most of the Late Cretaceous and Paleogene.

The extinction event at the K–Pg boundary occurs after a period of low extinction and speciation rates in the latest Cretaceous, with a net diversification close to zero (Fig. 2c). The extinction phase involves an interval of 5.4 Myr (66.9–61.4 Myr ago; Fig. 2b). The fact that the first shift in the extinction rate slightly predates the K–Pg boundary is likely a result of the stratigraphic binning of the fossil record being too coarse to precisely date the onset of the extinction event. The extinction event is accompanied by a peak in speciation about as high (Fig. 2b). While the extinction rate drops to a low level at 61.4 Myr ago (95% confidence interval: 61.1–64.3 Myr ago), the speciation rate remains comparably high for the next 6.9 Myr (3.6–8.7 Myr) until it drops to a similar level as the extinction rate. From 55.1 Myr ago (53.8–56.9 Myr ago) onwards – 11.8 Myr after the onset of the event – the net diversification rate is back to Late Cretaceous background level.

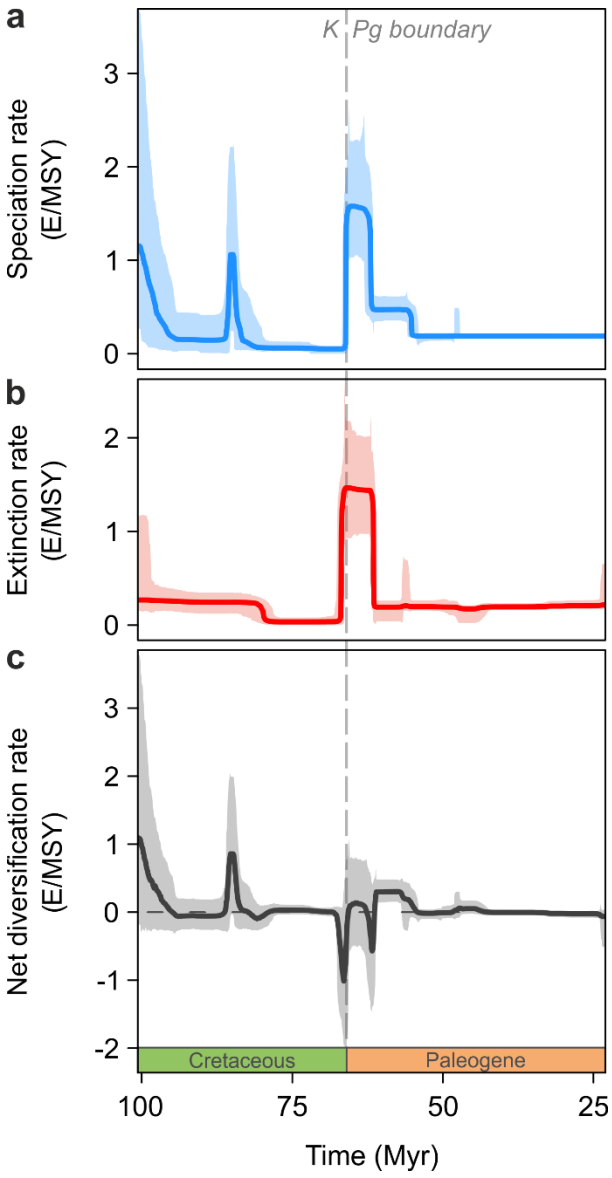

Fig. 2 | Rates of diversification of European freshwater gastropods. a, Speciation rate. **b**, extinction rate. **c**, net diversification rate, calculated as speciation minus extinction rate. Shown are the median rates and the 95% highest posterior density quantifying the uncertainty in rates. Here we focus on the Late Cretaceous and the Paleogene; the complete version is shown in Extended Data Fig. 2. E/MSY, events per million species years.

Predictions for the current biodiversity crisis based on conservation statuses of 347 extant European freshwater gastropod species assessed by the IUCN Red List[34] indicate much higher extinction rates than for the K–Pg event (Supplementary Data 2). Extinction rates range between 1378.9 (1316.7–1441.1), 1787.1 (1733.3–1840.8) and 1973.2 (1923.4–2023.0) E/MSY (events per million species years) over the next 50, 80 and 100 years, respectively (Fig. 3). This is approximately three orders of

magnitudes higher than the extinction rate during the K–Pg event (~1.45 E/MSY; Fig. 2b) and reflects the extremely fast pace of the current biodiversity crisis. Further, the simulations indicate that between 72 (20.8%) and 111 species (31.9%) might go extinct during the next 50 to 100 years (Fig. 3). If this trend is projected into the future, the 75% extinct species threshold defining a mass extinction[17] would be reached already by the year 2539 (95% confidence interval: 2527–2551). Accordingly, the 6th mass extinction would involve less than a millennium, at least from the perspective of freshwater gastropods.

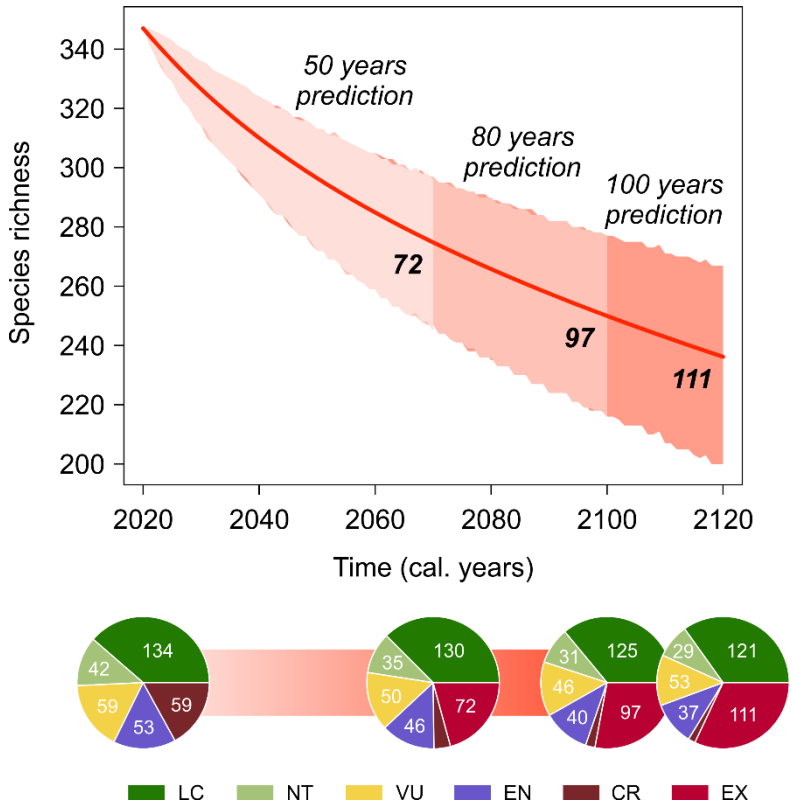

Fig. 3 | Extinction risks of extant European freshwater gastropods. Predicting the number of extinct species and conservation status change over the next 50, 80 and 100 years based on current species conservation status as derived from the IUCN Red List[34] using the approach of Andermann et al.[35]. The graph shows the results from the dataset excluding species with little fossilization potential (spring, subterranean, cave and karstic species) to facilitate comparison with the results from the diversification analyses. The results of the analysis based on the complete fauna are provided in the Supplementary Data 2 and Extended Data Fig. 3.

Discussion

Freshwater extinction at the K–Pg boundary was severe and has been underestimated so far. Previous studies based on the vertebrate fossil record reported freshwater species extinction levels of 10–22%[25]. However, our new estimates based on freshwater gastropods show a species richness decline of 92.5% and an extinction rate being more than an order of magnitude higher than background level. This magnitude is even higher than the global average of the 5th mass extinction event, which wiped out approximately 76% of all species on Earth[17]. As such, freshwater gastropods line up with major terrestrial and marine animal and plant groups that experienced strong decline in species richness or disappeared entirely. This concerns, for example, non-avian dinosaurs, ammonites, bivalves, ostracods, planktic foraminifera, calcareous nannofossils, bryozoans and land plants[19,38–41].

The 5th mass extinction event shares several features with the current crisis, making it a potential model system to investigate and predict biotic response to the catastrophic environmental turnover we observe today. During both the latest Cretaceous and the late Cenozoic, a global cooling trend is followed by steep and rapid temperature increase driven primarily by rising CO_2 levels[20–23,42]. Both intervals witness concerted biodiversity decline in many taxonomic groups[29,43,44] (see also Fig. 1), but peaks in extinction rates coincide with catastrophic events. The current biodiversity crisis is largely the result of human impact[6,12,16,45–47], and its tempo (decades to millennia) is that of an instantaneous event in terms of the geological record. Thus, one may consider the catastrophic event at the K–Pg boundary a suitable parallel for the current, anthropogenically driven crisis.

Comparing our reconstructions of diversification dynamics and extinction magnitude for the 5th mass extinction event with the predicted future trends of the current biodiversity gives deeply worrying prospects. Freshwater gastropod extinction rates are estimated to be approximately three orders of magnitudes higher than for the 5th mass extinction event (1378.9 to 1973.2 versus 1.45 E/MSY), indicating a much faster pace of extinction than at the K–Pg boundary. These values are in a similar range as previous estimates for the current biodiversity crisis[12,17,46]. According to our model, 75% of all European freshwater gastropod species might be lost before the end of the millennium, if the current trends are not reversed. If human impact – either directly via habitat degradation or destruction, eutrophication or pollution or indirectly through climate change – continues to increase as predicted[11,16], the mass-extinction-threshold of 75% will be reached even earlier.

The aftermath of the 5th mass extinction event also implies an extended recovery period for the current crisis, which will probably last millions of years. Even after the immediate cause of extinction at the K–Pg boundary ceased (i.e., the asteroid impact and extreme weather conditions in the successive months/years), the extinction rate remained high for 5.4 Myr and the subsequent recovery period involved another 6.9 Myr. Altogether, it took approximately 12 Myr until net diversification returned to the Late Cretaceous level (Fig. 2). Gastropod species richness took approximately 7–8 Myr to recover (Fig. 1). Translating this to the current biodiversity crisis suggests that even if anthropogenic impact on the world's biota ceases immediately, the phase of extinction might still involve several million years and so will faunal recovery[48,49]. Given the extremely fast pace at which global change happens today and the high rates of extinction predicted for the next decades, both of which outpace the rates for

191 the 5th mass extinction, freshwater biota may face an even more dramatic collapse in
192 the near future than after the asteroid impact 66 Myr ago.

193 The ongoing extinction crisis has consequences on many levels. For individual
194 ecosystems, the loss of species comes with an inevitable change in community
195 composition. Species perform specific functions in ecosystems and – depending on
196 their role and interactions with other species – their extinction or local extirpation may
197 have immediate causes on the ecosystem stability or functioning[45,50–52]. Radical
198 changes in ecosystem functioning, in turn, may have severe implications on
199 ecosystem services for humanity, such as food provision, disease resistance or
200 economic benefits[11,45,48]. Thus, if we continue to lose species at the fast pace our
201 analysis suggests, we will continue to impair ecosystem services to our own
202 disadvantage.

203 In summary, our study clearly evidences the vulnerability of freshwater biota to past
204 and current extinction crises and implies a long aftermath in case we cannot mitigate
205 it. We show that rates of extinction are by one (66 Myr ago) or four (today) orders of
206 magnitudes higher than background level. 92.5% of all freshwater gastropod species
207 went extinct during the 5th mass extinction, which entailed an extinction phase lasting
208 5.4 Myr and a subsequent recovery period lasting further 6.9 Myr. The current
209 biodiversity crisis appears even more drastic, with species being lost at a much faster
210 pace. Our analyses suggest that 75% of all European species may be lost within
211 centuries. Hence, our results support the notion by previous studies[17,18] that we are
212 heading towards a 6th mass extinction event, and we may reach it before the end of
213 the millennium. Our findings provide yet additional evidence that immediate and
214 effective action is needed to protect biodiversity.

Methods

Fossil occurrence data. Given the inequity in species richness and distribution of the freshwater gastropod fossil record across the planet, we focus on Europe as target region. The European fossil record is well studied as evidenced by a rich and long research history and provides a high number of species and good geographic coverage (Extended Data Fig. 1, Supplementary Data 1).

Locality-based freshwater gastropod occurrence data for the Jurassic–Pleistocene (201.3–0.0117 Myr ago) of Europe were assembled from the literature and selected collection sources (Extended Data Fig. 1, Supplementary Data 1). Most data for the Neogene and Quaternary derive from Neubauer et al.[29] yet incorporating recent taxonomic revisions and additions. The geographic delimitation of Europe follows that study and includes Anatolia and the Caucasus region; in the east, it is bounded by the Ural Mountains. Data from western Turkmenistan and Kazakhstan were included if associated with the biogeographic realms of the Caspian Sea and Paratethys Sea, respectively.

We focused on the species as basic entity for estimating diversification rates. Diversity reconstructions in deep time have been typically performed on genus- or family-level data[44,53], but especially for stratigraphically old faunas, such as the early relatives of modern clades back in the Jurassic and Cretaceous, genus or even family classifications are often doubtful. Species are typically binned into common genera, which may greatly bias actual genus ranges. Similarly, many Mesozoic species lack sufficient diagnostic features that allow clear assignment to a specific family.

Uncertain records (“cf.”), nomina nuda, nomina dubia and taxa inquirenda were excluded. Taxa with temporary names were included; although their names might not be accepted at present (e.g., being junior homonyms pending revision), they still represent valid species. We implemented taxonomic revisions to account for changes to species lists, synonymizations, correction of misspellings and changes of taxon rank and systematic classification. To assure a sound age classification of the fossil occurrences, we used most up-to-date stratigraphic information for the fossil-bearing strata and accounted for revisions in regional stratigraphic schemes and lithostratigraphic and biostratigraphic correlations. Ecologically, we included obligate freshwater as well as oligohaline taxa; mesohaline (e.g., mangrove or estuary) species were excluded.

In the end, the data were critically reviewed by the authors, some of which are experts in non-marine gastropods taxonomy and systematics as well as stratigraphy. Selected records or faunas that appeared highly doubtful due to severe taxonomic or stratigraphic discrepancies were excluded to avoid bias from misidentifications. The final dataset includes 24,759 occurrences of 3,122 species in 5,564 localities (Extended Data Fig. 1, Supplementary Data 1).

Despite the huge amount of data available, extant European faunas were not considered in the present study for a number of reasons: 1) Preliminary analyses have shown that the discrepancy in the number of records available for fossil and recent faunas in relation to their stratigraphic ranges complicates the inference of the diversification rate; analyses regularly fail to converge even when using a high number of generations. 2) Taxonomic and species concepts tend to vary between neontologists and paleontologists, owed to the different preservation and species

traits of the material available to them. Including both sources of data will inevitably result in taxonomic biases. 3) The selective preservation towards lacustrine or lowland faunas in the fossil record[28] complicates comparison with the recent fauna. Accordingly, we limited the dataset to pre-Holocene records.

Inferring the diversification rate. In order to account for age uncertainties, we generated 200 randomized data sets by resampling the age of each occurrence uniformly within the respective temporal range, following the procedure described by Silvestro et al.[54]. Analyses were performed using the Python-based open-source program PyRate developed by Silvestro et al.[54] (https://github.com/dsilvestro/PyRate). Rate estimates from the fossil record were based on the probabilistic model proposed by Silvestro et al.[54]. Fossil occurrences are modeled as the joint result of preservation potential (i.e., the probability of sampling at a given time and including its heterogeneity across species), speciation and extinction. Sampling is modeled as a time-variable Poisson process according to stratigraphic epochs, with the exception of constraining a time-invariable sampling rate for the Early and Middle Jurassic because of the paucity of records for these time intervals. We inferred species diversification by a recently developed Reversible Jump Markov Chain Monte Carlo (RJ-MCMC) algorithm with time-varying speciation and extinction rates, where rates are allowed to shift over time[54].

Analyses were divided into two steps. Firstly, to obtain posterior estimates on speciation and extinction times, we ran the analyses with 200,000,000 MCMC iterations at a sampling frequency of 20,000, discarding the first 20% as burn-in. From each resulting MCMC log-file, three posterior samples of speciation and extinction times were extracted. The resulting 600 replicates of speciation and

extinction times were used in a second round of analyses to infer the number of rate shifts. We checked the effective sampling size (ESS) with the 'coda' package 0.19-3[55] for the statistical programming environment R 3.6.3[56] and base all our observations and interpretations on the 100 log-files with highest ESSs (i.e., ESS for birth–death likelihood of > 100 and ESSs for posterior, prior, the number of sampled rate shifts, and hyperprior of > 90). We calculated the extinction magnitude across the K–Pg boundary as the percentage of taxa that originated before the event but became extinct during the event (which is defined by two shifts in the extinction rate; see Fig. 2c).

Predicting future extinction magnitude and rates. We used the recently developed approach of Andermann et al.[35] to simulate future extinctions based on conservation status information according to the IUCN Red List[34]. We queried the IUCN Red List for freshwater gastropods occurring in European countries (including Caucasus countries as well as Turkey, to cover the same geographic scope as the fossil dataset). Taxonomically, we included the families listed by Cuttelod et al.[30], excluding the semiaquatic families Assimineidae and Ellobiidae. Only extant resident species were included; extinct, possibly extinct and introduced species were omitted. For the final dataset, we excluded species occurring exclusively in caves, springs and karstic or subterranean environments. Species living in these habitats have little fossilization potential[28] and including them would impede a reliable comparison with the estimates from the fossil dataset. These filters yielded 347 species with valid conservation statuses. Nonetheless, to allow comparison with other datasets and faunas, we carried out the same set of analyses also on the dataset including the entire fauna (881 species); the results are provided in the Supplementary Data 2. The

310 R package ‘rredlist’ v. 0.6.0[57] was used to collect the status history and most recent
311 conservation status for each species.

312 The dataset was analyzed using the Python-based program ‘IUCN Extinction
313 Simulator (iucn_sim)’ developed by Andermann et al.[35], which is freely available at
314 https://github.com/tobiashofmann88/iucn_extinction_simulator. The analysis models
315 future changes in conservation status for each species based on estimates of status
316 transition rates, allowing predicting the number of species that will become extinct
317 over a defined time interval. For species marked as ‘Data Deficient’ (DD), a new valid
318 status is drawn based on randomly sampling 100 transition rates for all transitions
319 from DD to any of the statuses LC, NT, VU, EN and CR[35]. Here we applied the model
320 for three time intervals: 50 years, 80 years (corresponding to year 2100) and 100
321 years (as in Andermann et al.[35]). Based on the model, we calculated the mean
322 duration until the extant fauna reaches the 75% extinction level, which marks a mass
323 extinction according to Barnosky et al.[17]. Additionally, we employed an MCMC
324 algorithm as implemented in iucn_sim using 100,000 generations (discarding the first
325 5,000 as burn-in) and 50,000 simulations to infer rates of extinction based on the
326 three simulated future extinction models (using the ‘EX mode 1’ algorithm of
327 Andermann et al.[35]).

328 Andermann et al.[35] showed that predictions become more accurate when accounting
329 for conservation status history and information on species generation lengths.
330 Unfortunately, we lack both; there are hardly any changes recorded by IUCN Red
331 List[34] as concerns the conservation statuses of European freshwater gastropod
332 species since the first assessments in the 1990s and there is insufficient knowledge
333 about generation lengths of the 347 species. Nonetheless, an analysis excluding the

available conservation status history showed that this has a limited effect on the outcome (115.0 vs. 110.8 extinctions for the 100-year scenario; see Supplementary Data 2).

Data availability

All data are included as Supplementary Data.

Acknowledgements

Computational resources were provided by the BMBF-funded de.NBI Cloud within the German Network for Bioinformatics Infrastructure (de.NBI). We are grateful to Burkhard Linke for assistance during the cloud setup; to Tobias Andermann for assistance with the predictions based on IUCN data; to Wolfgang Brunnbauer, Sebastian Calzada, Daniela Esu, Joachim Gründel, Sonja Herzog-Gutsch, Olaf Höltke, Arie W. Janssen, Ronald Janssen, Eike Neubert, Jean-Michel Pacaud, Sophie Passot, Simon Schneider and Maxim Vinarski for providing literature.

T.A.N. was supported by a Just'us Fellowship, an Alexander-von-Humboldt Fellowship and a DFG grant (NE 2268/2-1). D.S. received funding from the Swiss National Science Foundation (PCEFP3_187012; FN-1749) and from the Swedish Research Council (VR: 2019-04739).

Author contributions

TAN and TW designed the study; TAN, DK and MH collected and reviewed data on species occurrences, taxonomy and stratigraphy; TAN, TH, JS and DS performed the analyses; TAN led the writing of the manuscript; all authors contributed to the writing and the interpretation of the results.

Competing interests

The authors declare no competing interests.

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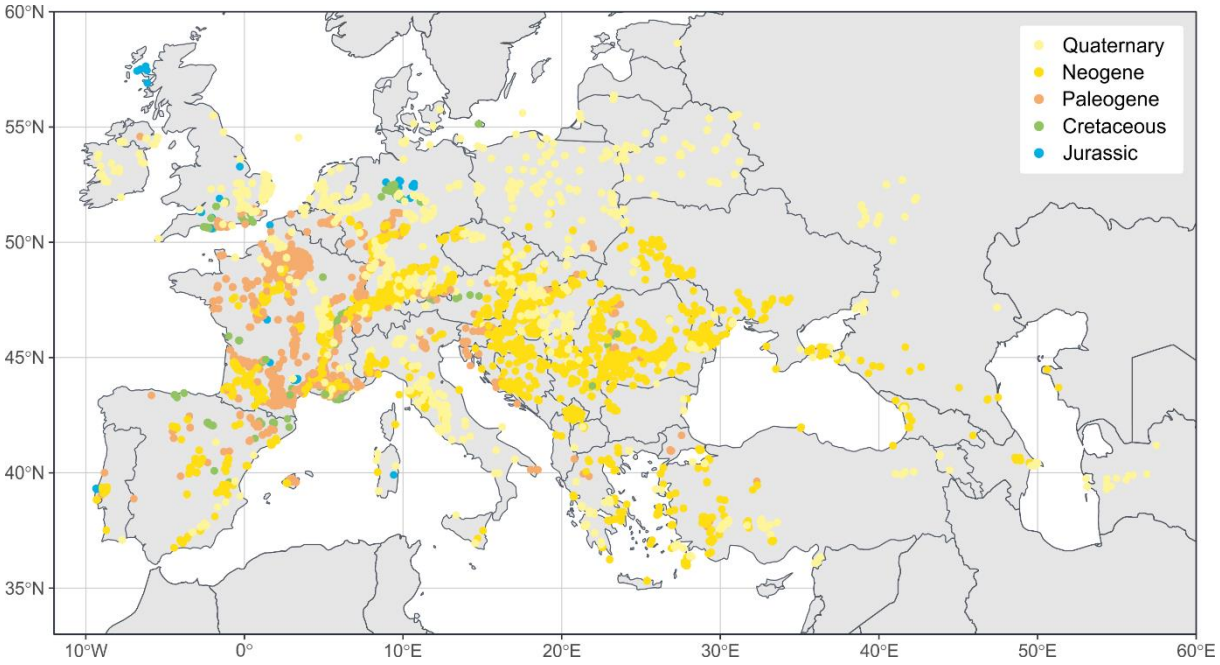
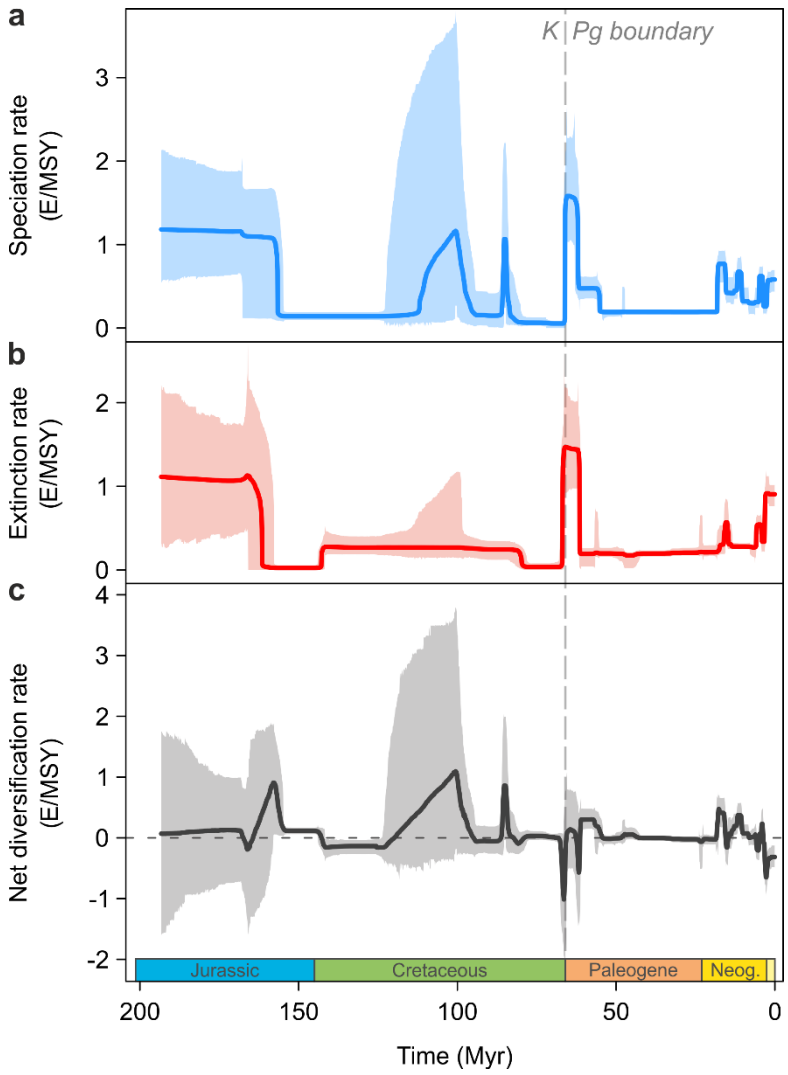
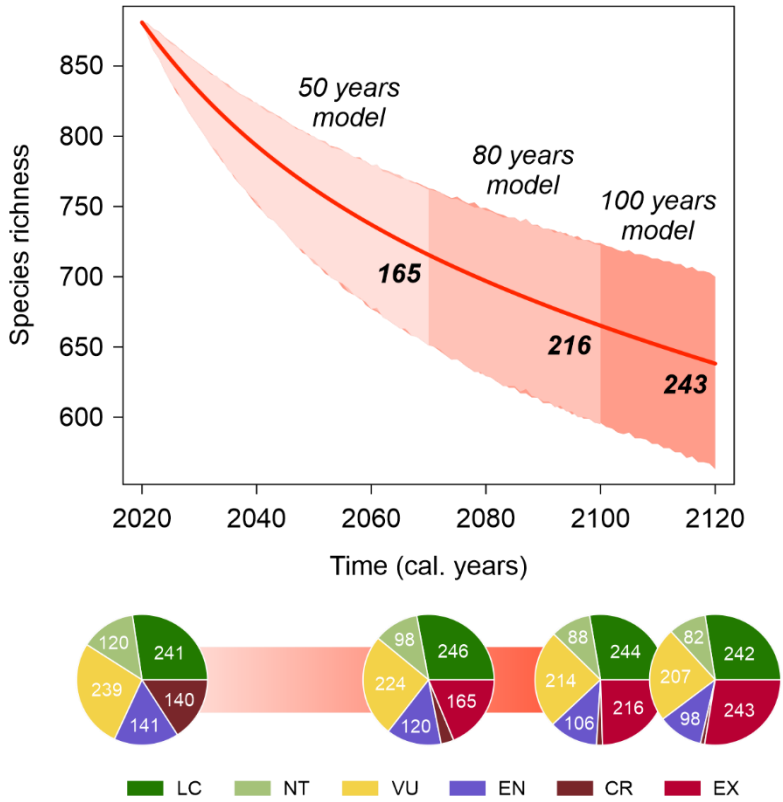


Extended Data Fig. 1 | Geographic overview of the dataset. Shown are the 5,564 localities yielding Jurassic to Pleistocene freshwater gastropods included in the dataset. Color codes conform to the International Chronostratigraphic Chart 2020 (freely available from https://stratigraphy.org/chart).



519 **Extended Data Fig. 2 | Rates of diversification of European freshwater gastropods. a**, Speciation
520 rate. **b**, extinction rate. **c**, net diversification rate, calculated as speciation minus extinction rate
521 (complete version of Figure 2). Shown are the median rates and the 95% highest posterior density
522 quantifying the uncertainty in rates. Net diversification is calculated as speciation minus extinction rate.
523 In addition to those in the studied interval (Figure 2), there are notable peaks in the speciation and
524 extinction rate in the Neogene and Pleistocene. The Neogene diversification pattern is likely a result of
525 the major radiations in several long-lived lakes in the Miocene, which is also mirrored in the
526 extraordinarily high diversity during this time period[29] (Figure 1). The high extinction rate at the Plio–
527 Pleistocene transition reflects the disappearance of these environments and faunas; the Pleistocene
528 plateau in the extinction rate is likely due to the massive climatic change during the glacial cycles[29].
529 The high rates inferred for the Jurassic may be a result of limited sampling. E/MSY, events per million
530 species years.



Extended Data Fig. 3 | Extinction risks of extant European freshwater gastropods. Predicting the number of extinct species and conservation status change of the complete European freshwater gastropod fauna (including spring, subterranean, cave and karstic species) over the next 50, 80 and 100 years based on current species conservation status as derived from the IUCN Red List[34] using the approach of Andermann et al.[35]. The results of the analysis are provided in the Supplementary Data 2.

Point-by-point response to the reviewer's comments

Reviewer #1

Neubauer et al. present an assessment of the severity of the Cretaceous-Paleogene extinction in fresh water gastropods, and compare it with projections of extinction rates in the next decades and centuries. The conclusion is that current/future extinction of freshwater gastropods is and will be ~1000 times as severe as the K-Pg one. The methodologies applied seems robust for each of the contexts used: the K-Pg and current/future gastropods depletion. Overall, the manuscript is well written and the hypothesis feel presented. However I have a fundamental concern around how K/Pg and current extinctions are compared.

In this study, extinction estimates from occurrence data and extinction estimates from current IUCN Red List risk categorizations are put one in front of the other like they are comparable. And they are far from comparable. Many factors render this one an unfair comparison. IUCN lists most of current diversity, even relic species with tiny geographic ranges, or those with low population densities. In fact, having a tiny geographic ranges and low population densities are good candidate features ensuring a given species ranks high in extinction risk. But also, it is the case that these species are very unlikely to leave abundant fossil remains that will be preserved, exposed and collected 66 million years into the future (assuming there are paleontologist in that future).

What I mean is that, in the same way that we take sampling biases into account when estimating extinction rates from fossils, Neubauer et al. should take sampling biases into account in the current+future extinction models. This is especially interesting given that their paleo-derived extinction curve shows a dramatic increase in extinction in the last 5 million years. So the key question is: acknowledging that species higher in the IUCN rank will most probably never make it as fossils, how much will future extinction departure from the severe extinction peak estimated for the last 3 million years (~0.8 E/MSY)?

Because "today" we see (and the IUCN evaluates) the results, not only of human activities, but those of this Quaternary extinction peak the most severe in the last 60 million years. Importantly, species high up in IUCN risk categories would already appear as extinct if a paleontologists would conduct PyRate with today's occurrences 65 myrs into the future. Thus the first step for a fair comparison is to use IUCN data in a way that accounts for a decreasing sampling probability with higher extinction risk.

We thank the reviewer for the constructive feedback on our manuscript. The potential bias towards small-ranged taxa indeed can be a major problem, particularly when comparing fossil and modern data. However, we think that downgrading the (quite good) IUCN data to make it comparable to a naturally biased fossil record would rather worsen the results. Rare and small-ranged taxa are a universal component of biota (Hubbell 2001). Having such taxa included in a dataset demonstrates its completeness and make the estimation of extinction rate reliable.

Fossil data are in our opinion more critical than extant species as they are inherently biased towards more abundant and large-ranged taxa. To address this issue, we used a preservation model with

sampling rates allowed to vary through time and across taxa when estimating the diversification rates, which specifically accounts for the varying abundance of records in different time periods. Moreover, just like the IUCN data, our dataset shows a good spread of highly abundant species as well as a high number of endemic species (including many point-endemics) – 14% of the species are found in more than 10 localities and 39% of the species are only found in a single locality. This variable frequency (in combination with a good geographic spread of the data; see Supplementary Figure 1) also shows the high quality of the fossil dataset.

Since the issue concerning the comparability of the fossil and extant datasets particularly concerns the second point raised by Reviewer #1 (see following paragraph), further strengths of our dataset showing that a fair comparison is indeed possible are detailed in the following section.

Further issues obscure a straightforward comparison. Paleontological species are not comparable to current species. Many living species would not be differentiated based on their paleontological remains. Current diversity, and thus E/MSY units, are not comparable either. This is a tricky problem, Barnosky et al. 2011 suggest to clump living species into genera for a fair comparison.

The suggestion of Reviewer #1 to use genera instead of species for the modern fauna reflects the common problem of comparing neontological and paleontological data. Indeed, the two datasets could be challenging to compare and therefore we have gone to great lengths to curate the data to allow for a meaningful comparison.

We were very careful in the selection of our fossil dataset in the first place. The dataset was not retrieved from an online database or assembled uncritically from the literature. We individually set up a database and have curated it for several years. Each of the >25,000 records was personally entered and cross-checked by us. Since several of us are also taxonomists (T.A.N., D.K., M.H., F.W.), we subjected the data to a careful screening process, filtering out records that are questionable (in terms of species identification or doubtful geological ages).

To facilitate a sound comparison between extant and extinct species, we have already constrained the modern dataset to filter out those species that mostly likely would not yield a fossil record, e.g., species from caves, springs or groundwater (see lines 327–330 [with track-changes enabled]). However, we performed another set of analyses including those species to test if the data selection has an influence on the extinction rate; the patterns found are very similar though (see Supplementary Tables 5–7 and Supplementary Figure 3). Moreover, the PyRate analyses of the fossil species accounts for preservation issues in the fossil record, which makes the rates inferred from the two different analyses and datasets indeed comparable.

Furthermore, the genus-level comes with a conceptual problem in biology/paleontology. As pointed out by Hendricks et al. (2014) “genera are arbitrarily circumscribed, non-equivalent, often paraphyletic, and sometimes polyphyletic collections of species [that have] no theoretical or biological reality of their own.” Hendricks et al. specifically tested the impact of using genera instead of species and found strong evidence for a bias. They concluded that “evolutionary studies that are actually about species should be pursued using species-level data rather than proxy data tabulated using genera.” In the revised version, we slightly expanded upon the choice of systematic level and

specifically refer to the paper by Hendricks et al. in the Methods. Also, we show in Figure 1b the massive discrepancy between the extinction magnitude on the species and genus level: compared to 92.5% of all species, only 9.5% of the genera go extinct. This shows that using genera instead of species would obscure the magnitude of the K–Pg extinction. In fact, the use of higher taxonomic level might be a potential reason why the severity of the K–Pg event has been largely underestimated in freshwater biota.

We believe the bias would be even more severe when comparing extinct species with living genera. Of course, we understand the difficulties in comparing species introduced based on different species concepts (e.g., morphological versus biological/phylogenetic). However, many extant species are still described based on morphological characters. Similarly, some fossil species were distinguished based on elaborate statistical methods to quantify shell shape, while others were described based on few qualitative characters. As such, there is some degree of variation within both neontological and paleontological data, and probably no method exists to fully overcome these issues.

We are aware that many studies use the genus-level for their analyses, however there is a strong trend to use species-level data (e.g., Silvestro et al. 2015, Lim & Charles 2017, Law et al. 2018, Pimiento et al. 2020, Wilke et al. 2020). Andermann et al. (2020) made a similar comparison of fossil and recent species as we did, also inferring extinction rates of fossil species with PyRate and making predictions with iucn_sim based on IUCN data of extant species. We expanded the part in the Methods section to discuss this issue (lines 256–258).

Nevertheless, we understand the importance of testing how robust our result is with respect to the systematic level. The analyses of near-future extinction cannot be simply conducted on genus-level because genera do not have IUCN conservation statuses. Therefore, we added a new analysis in the revised version of our manuscript, where we inferred the extinction rate on genus-level by obtaining the extinction date for each and every species and then calculating the inverse of the mean extinction date of the genera's last survivors (see lines 362–374).

The average genus extinction rate is 1018.7 (852.0–1199.6) E/MSY. This rate is unsurprisingly lower than that for the species-level analyses, i.e., 1973.2 (1923.4–2023.0) E/MSY, since more than half of the genera in the IUCN dataset contain at least one non-threatened species. The probability of these genera to go extinct is naturally lower than for the individual species.

The overall result still ranges in the same order of magnitude as the species-level analyses and is almost three orders of magnitude higher than the inferred extinction rate during the K–Pg event (~1.45 E/MSY). This shows very clearly that our results based on species-level data are robust and do not depend on the systematic level.

In summary, considering our careful taxonomic screening process paired with a good knowledge of the species we are dealing with, suitable and robust analyses accounting for potential biases and uncertainties, as well as a cautious selection of the modern dataset, we believe we have addressed taxonomic issues and inequalities as effectively as possible. These points are also thoroughly discussed in the Methods chapter to demonstrate the comparability of the two datasets. We also include the new genus-level analysis requested by Reviewer #1 in the paper (see lines 128–133 and 362–374).

So, for such a fair comparison, I think the authors should at least address these two facets. They must aggregate living species into genera first (or some other and less straightforward grouping into morphospecies), and then subject their IUCN to a sampling downgrading. This could be added to the risk categories transition model. For example, advances in this rank will entail an exponential decrease in sampling probability, bearing in mind that not even all widespread species leave fossils… Of course, current categories should also be linked to this exponential decrease in sampling probability and species should be resampled from this probability of being sampled for current and future estimates of extinction. This means that as we advance in LC, NT, VU, EN, CR and EW, these should see a dramatic decrease of the odds of being included in the analyses. If DD and NE species did not make it to the Red List, we can assume that they would have never made it to the fossil record.

Then use all this to ask whether the Quaternary extinction peak we are surfing right now will get significantly worse and we should add another shift/peak in the extinction curve of Extended Data Fig. 2.

> We believe we have addressed both points criticized by Reviewer #1. As requested, we have performed a new analysis to predict future extinction rates based on genera instead of species. The similarity of the outcomes supports the robustness of the results of our species-level analysis. Considering the high quality of the fossil and modern species datasets, as well as conceptual shortcomings of the genus-level, we still think the species-level is the better choice to infer extinction rates. In the revised version, we focus on the species-level results, but we also include the new analysis and results of the genus-level data (see lines 128–133 and 362–374).

Reviewer #2

This paper has been based on the authors extensive knowledge on European Mesozoic and Cenozoic freshwater gastropods.

I fail to find any major errors in their methodology, their data and their conclusions as well as in their basic hypothesis that the coming 6th mass-extinction in European freshwater gastropods may be worse than the 5th mass-extinction.

Therefore, this paper responds to all requirements to be accepted for publication. I do however retain a single question: namely can or should a global extinction event in the future be compared to a global extinction event in the past, based on the evolution of the gastropod fauna of a single continent from the Late Mesozoic to the present?

> We thank the reviewer for the thorough and constructive feedback. We agree that a conclusion on global extinction patterns is not possible from a single continent. Therefore, we have reduced our interpretation to European faunas in our revised manuscript (see especially lines 149–154, 224–228). Since mass extinctions usually affect biota not only on a global scale but also on a continental

level, we believe the comparison between the effects of the 5th and 6th mass extinction events on the European biota still provides vital insights into long-term evolutionary processes.

After all, restricting the dataset to Europe has one big advantage. Both the fossil record (see also below) and the modern data are most comprehensive for this continent, as we now clarify in the revised Introduction and Discussion (lines 78–81, 149–154). Given the high number of specialists on European faunas, Europe's freshwater biota are better studied than those of other continents (e.g., Böhm et al. 2020). As such, IUCN data cover European faunas particularly well. Thus, limiting the analyses to Europe allows probably a less biased comparison between past and current/future extinction levels than a global analysis with many blank spots on the map.

In my opinion, the authors should at least provide some arguments why specifically Europe has been selected as a pars pro toto. For this single-continent-approach raises several issues:

- (1) in the period under consideration (Jurassic to Pleistocene), Europe was not isolated but joined with either N. America or with Asia or with both. At some points in the geological history, it may be possible to speak of a distinct European malacofauna, on others it is not so evident.

Indeed, the isolation of the European fauna was tricky in some cases. The North Atlantic, separating Europe and North American, opened in the early Cenozoic (Torsvik et al. 2019), but even before the two continents were well delimited by shallow seas (see, e.g., Cao et al. 2017). Similarly, the Ural Mountains delimiting Europe from Asia have existed already at least since the Triassic (Gradstein et al. 2012) and intercontinental seas have isolated Europe from the rest of Asia during most times (Cao et al. 2017). The available Mesozoic faunas come from central or western Europe (Supplementary Figure 1), and there is no doubt that the respective regions back then belonged to what forms Europe today. Faunas from the same geological age in North America (e.g., Henderson 1935) and Asia (e.g., Martinson 1961, Pan 1977) show very different compositions, suggesting clear biogeographic boundaries across time. We added a paragraph to clarify this in lines 243–248 of the Methods section.

- (2) in N. America (Hartman et al., 2002, Justham, 2008, Hartman, 2015) and in SE Asia (see e.g. Yu et al., 2021), the fossil gastropod records of the Cretaceous-Paleogene transition are better preserved than in Europe. Though I could be mistaken, I do not have the impression that the shift in species composition between the end-Cretaceous and the Early Paleogene was so dramatic on these continents as the one based in the present paper on European data.

As Reviewer #2 points out, there are several North American faunas spanning the K–Pg boundary (e.g., White 1879, Henderson 1935, Tozer 1956, Hartman 1998; in addition to the ones cited by Reviewer #2). However, compared to Europe, the North American fossil record is still rather sparse and the geographic spread is more uneven. Most of the pre-Pleistocene fossil record is restricted to the western United States and southwestern Canada (e.g., Henderson 1935). Apart from these issues, no large-scale evaluation of these faunas exist. We cannot estimate if or how much the K–

Pg event affected those faunas without a detailed assessment and diversification analyses. This subject is certainly worth a closer look and might help to test whether the pattern we found for Europe is a general one.

In comparison, Europe has an exceptionally rich fossil record with more than 3100 species. In contrast, the MolluscaBase database (http://molluscabase.org/), for which the lead author is a taxonomic editor, lists approximately 500 fossil freshwater gastropod species for North America (Triassic to Pleistocene).

The picture for Asia is unfortunately even worse. The study by Yu et al. Reviewer #2 refers to was co-authored by the lead author, who got quite good insight into the Asian fossil record in the course of that study (as well as during entering fossil species to MolluscaBase; see above). There are much fewer studies available for Asia and the geographic spread of faunas is even worse than for North America. Also, the taxonomy and systematics of many of these faunas is poorly resolved, and so is the stratigraphy in many cases. An assessment how much the K–Pg event affected those faunas cannot be reliably reconstructed from the available data.

Much fewer species and records are known for Australia, Africa and South America and their distribution in space and time is patchy at best.

We see the importance of discussing our findings in a broader context and added paragraphs in the Discussion accordingly (see lines 149–154, 224–228; see also response to the comments of Reviewer #3).

- (3) In the fossil records of other continents, the most marked difference in the composition of the freshwater molluscan fauna before and after the 5th mass-extinction, seems to be the shift from assemblages dominated by or often exclusively consisting of bivalves to assemblages consisting mainly or exclusively out of freshwater gastropods.

This is an interesting idea and certainly worth pursuing in future studies. Especially unionid bivalves seem to be very speciose during the Mesozoic (e.g., van Damme et al. 2015). Again, there are no data available to allow for a sound comparison, but having screened through many hundreds of publications on fossil mollusk faunas (including many bivalve faunas as well), our impression is a slightly different one. Bivalves seem to be particularly diverse in the earlier Mesozoic, when freshwater gastropods were still scarce (or poorly preserved) and some families have not even evolved (Taylor 1988). Yet, when comparing the number of bivalves and gastropods across the K–Pg boundary in North American formations (e.g., as summarized in Tozer 1956), there are still more species of gastropods both in the latest Cretaceous and early Paleocene. Whether the same is true for other continents cannot be reliably reconstructed, considering the poor quality of the fossil records there (see above). Therefore, we refrain from diving into this subject in the present paper.

- (4) the number of European localities/assemblages of Cretaceous age is <40. Why localities/assemblages of Jurassic age, i.e. predating the K/P event > 100 My, have also been sampled, remains unclear to me.

Indeed, we focus in the present contribution only on the diversification pattern across the K–Pg boundary and the current biodiversity crisis. The reason for including fossils from before 100 Ma is the underlying phylogenetic diversification model following the birth-death process where species accumulate exponentially (as long as speciation rate > extinction rate) due to the splitting of an ancestral lineage into two descendants. Therefore, the initial number of occurrences and their age is of critical importance, which is why we included also older fossils. We admit that the evolutionary history of freshwater gastropods does not go back to a single common ancestor but to multiple colonization events of fresh water and dispersals in and out of Europe. However, as outlined above on the biogeographic isolation of Europe's gastropod fauna through time, these events are supposedly rather rare.

In conclusion, if feel that the authors need to provide a rationale why the effects of two world wide mass extinctions are compared on the basis of the effects on the freshwater gastropods of the European continent, though there exists ample evidence that the effects of the K/T extinction were not identical on all continents.

We think this point is now addressed in our revised paper.

Reviewer #3

The authors analyse extinction rates on fossil freshwater gastropods from Europe, from the late Cretaceous to the Pleistocene-Holocene, and extinction rates on extant freshwater molluscs of Europe based on the status information on the IUCN Red List. The objective is clear, and the method is well explained, but some statements should be revised.

The major issue that I found (see further comments on manuscript pdf file) is the concept of mass extinction that is used along all the paper. The authors claim that the freshwater fauna was affected by the 5th mass extinction in a larger rate than traditionally accepted (from a ~ 20% to a ~ 90%), and that their results can prove that we are now having a 6th mass extinction. Both statements possibly may be true, but they cannot be fully demonstrated with this data, that comprises only freshwater gastropods from Europe. To characterise a mass extinction, it must be considered biota from all over the world, and Europe is a small part of the continental areas on Earth. So, the results cannot be used in a straight form as a proxy to extrapolate these results for the rest of the planet (please, see comments on pdf file).

We thank the reviewer for the detailed and constructive feedback. This comment is in line with the argumentation of Reviewer #2 that we cannot conclude on a global phenomenon but have to limit our interpretation to Europe. We agree with this point and have revised the respective parts accordingly. We also changed the title as requested by Reviewer #3.

Besides, it would be useful to pay more attention to regional extinction events and species recovery rates during the climate changes over the Quaternary, as they probably are more alike to the present climate change than the extinction event in the K-Pg, where paleoclimatological and paleogeographical configuration were different from present.

We agree with Reviewer #3 that a brief comparison with the faunal developments during the Quaternary is useful and have added a paragraph to the Discussion accordingly (lines 173–180). However, we limited the comparison since the causes for the Quaternary and present crises are still largely different. Human impact has been shown to be an important driver of extinction of the Quaternary terrestrial mammals (Andermann et al. 2020), but it was probably of lesser significance for freshwater biota. Back then, climate change was very likely a main trigger. Conversely, today, direct human impact through habitat destruction/modification and pollution is the main threat to freshwater gastropods (Böhm et al. 2020).

It is true that the climatic and (bio)geographic conditions are different during the K–Pg event and nowadays, but the catastrophic nature and steep rises in extinction rates and magnitudes in both cases cry for a comparison. Therefore, and since both events are widely referred to as mass extinctions, we still believe a comparison of the present biodiversity crisis to the event 66 Ma is reasonable (while keeping in mind that we only deal with data from a single continent). Moreover, many review papers exist that compare other mass extinctions even though they have very different causes, outcomes and/or durations (e.g., Sheehan et al. 1996, Vajda & McLoughlin 2007).

In summary, this paper is important to call for a heads up for conservation of freshwater ecosystems of Europe, as extinction rates in freshwater gastropods are truly alarming, and that implies a modification in all the ecosystems. But, those results cannot be extrapolated and call them proof of a mass extinction, because a world-scale project, with data from other continents, (especially those with biodiversity hotspots) must be compared in order to do such statements.

Comments in PDF:

[p. 1] The title is misleading, I suggest: "Current extinction rate in European fresh water gastropods exceeds..."

Title changed as requested.

[p. 2] Extinction rates of fresh water gastropods in Europe increased...

We changed the respective part in the Abstract to make clear we are dealing with European data.

[p. 2] I will discuss this further in the document, but please, avoid claiming a 6th mass extinction as a result of this data. A mass extinction involves taxa from at least a great part of the Earth, and certainly Europe is not representative of the extant world biodiversity. For example, biodiversity is higher in the tropics, especially rainforest areas. That biome can not be found in Europe today. Moreover, the geographical area of Europe is a small percentage of global continental areas. Hence, in any case, this study is a valuable evaluation of regional extinction rates (that it is an important result by itself) but it cannot be extrapolated to a world scale event as a 6th mass extinction.

We agree and changed the respective parts accordingly – see also response above.

[p. 3] It is true that human activity is having a major impact on biodiversity worldwide, but comparing this fact with mass extinction events in the past is perhaps pushing the analogy too far. First because for past mass extinctions we have a better point of view than what is happening now, the human scale of observation is not an accurate one. It is more likely to compare the climate changes over the Quaternary with Anthropocene extinction than the K-Pg event. Some precautions have to be taken, for example, paleogeographic and paleoclimatological configurations of Earth are way too different in both events, starting during Cretaceous Earth was on a "Greenhouse" period and now it is on a "Icehouse" period.

(see second response to Reviewer #3's main points above)

[p. 4] See previous comment, it is not comparable

(see second response to Reviewer #3's main points above)

[p. 8] A claim about a 6th mass extinction involving only freshwater gastropods from Europe is not accurate. To claim a mass extinction event, it must be on a global basis, not a local one. Europe is a small portion of the planet, and despite the fact that its biodiversity is really well studied, it does not represent global biodiversity, so it can not be used as a proxy to extrapolate to the rest of the world. I suggest the authors to state that their results prove a regional extinction event, and that further studies (involving global species) must be done to know if this is happening on a global scale (probably is, but it can not be proven using these results).

As outlined above, we agree with Reviewer #3 and rephrased the sentence. As Reviewer #3 suggests, we refer now to a regional extinction event.

[p. 9] Again, this claim is only applicable for Europe freshwater gastropods. A major study involving global fossil records is needed in order to do such generalization. Please, rephrase clarifying that you are referring only to fossil species from Europe.

We added a paragraph after this one in the Discussion (lines 149–154) and a few sentences to the concluding paragraph (lines 223–228) to put our results into perspective and make clear that we are dealing with a single continent. We also discuss here briefly the problems associated with the fossil records of the other continents (see also above).

[p. 11] Not all freshwater gastropods, there is no evidence from this study to claim this statement. Please, rephrase that you are talking about European freshwater gastropods only.

Changed as requested.

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23rd Mar 21

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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I am glad to see that the authors have conducted a version of their analysis using a genera-version of current diversity. The extinction magnitud obtained from this version of the data remains significantly higher than the KPg peak. I believe this additional finding substantially strengthens the conclusion one the study. The effort in gathering the fossil dataset in this study is worthy of recognition, as it is the conceptual design and the methods. Much is to be explored about the potential IUCN categories to inform simulations of future sampling trends. Hopefully this will be implemented in newer versions of the iucn_sim software. In any case, studies like the present one pave the way to tackling a major task in paleobiology and conservation biology: a robust comparison of the current biotic crisis with past extinction pulses.

Reviewer #2 (Remarks to the Author):

In my opinion does the revised manuscript respond adequately to the comments formulated by referees #2 and #3. The taxonomic discrepancies between fossils and Modern gastropods, as pointed out by referee #1 remain pertinent but fall out of the scope of this study.

The revised manuscript is in my opinion suitable for publication

Reviewer #3 (Remarks to the Author):

Dear authors and editor, all comments were satisfactorily addressed, I have nothing else to add to my previous review. I recommend the paper to be published in its current state.
Kind regards